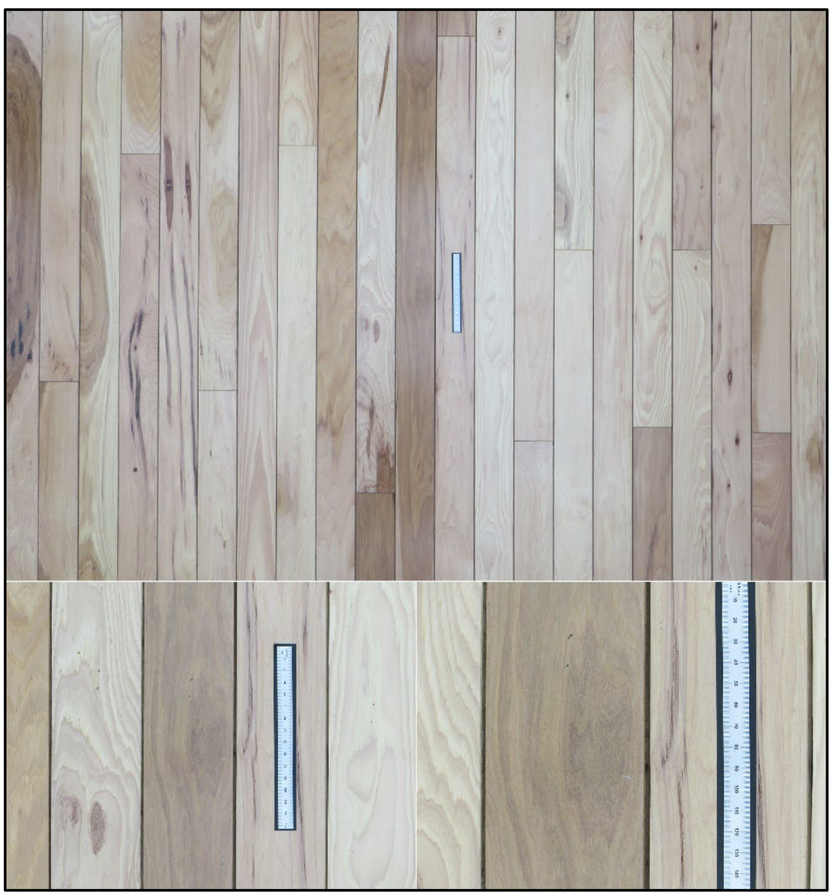
United States Department of Agriculture

Measurement and Practical Application of Tangential Dimensional Change Coefficients to Hardwood Flooring

Samuel V. Glass
C.R. Boardman
Prabu Ravindran
Alex C. Wiedenhoeft



Forest Service | Forest Products Laboratory | Research Paper FPL–RP–711 | June 2022

Abstract

Dimensional movement with changing moisture content is among the main performance characteristics of wood flooring. The U.S. wood flooring industry has relied on values and equations published by the Forest Products Laboratory (FPL) in its *Wood Handbook* to provide critical information about how different woods move. This paper discusses key information previously published by FPL relating to dimensional change coefficients (DCCs) and includes laboratory measurements of board width over a range of moisture contents for four types of prefinished commercial solid wood flooring: hickory, red oak, *Acacia* cf. *confusa*, and *Acacia* cf. *mangium*. Floorboards were initially conditioned to equilibrium at 80% relative humidity (RH), remanufactured to new target widths, and installed on subflooring assemblies according to industry guidelines. The assemblies were subsequently equilibrated at 30% RH and then again at 80% RH. Time-lapse videos are provided for each wood type, showing shrinkage and swelling with changing moisture content (MC) at two image magnifications. DCCs for installed floorboards were calculated based on measured widths and MCs at the two conditions. In addition, DCCs for uninstalled floorboards of the woods in this study were experimentally determined across a range of moisture conditions using two different calculation methods. Comparison of experimentally determined DCCs for uninstalled and installed floorboards indicates that there is no practical installation constraint on shrinkage of installed floorboards. No practical difference in DCC was found between tongue-and-groove floorboards and matched boards cut to a rectangular profile. Experimentally determined DCCs for hickory and red oak are within a reasonable range of *Wood Handbook* values, and we report the first published DCC values for the two *Acacia*. Reporting DCCs to two significant figures (rather than three) is recommended given the variability underlying the DCCs in the *Wood Handbook* and the variability in DCCs experimentally observed in this work. Practical methods for determining DCCs are discussed for species lacking published data. Incorporating variability in width measurement, MC, and DCC value in the calculation of moisture content at the time of manufacture results in a range of initial MCs that spans the actual MC, whereas using single, average values does not accurately predict the initial MC in three of four cases.

Keywords: Dimensional change coefficient, shrinkage, swelling, wood flooring, moisture content, *Wood Handbook*, hickory, red oak, *Acacia* cf. *confusa*, *Acacia* cf. *mangium*

June 2022

Glass, Samuel V.; Boardman, C.R.; Ravindran, Prabu; Wiedenhoeft, Alex C. 2022. Measurement and practical application of tangential dimensional change coefficients to hardwood flooring. Research Paper FPL-RP-711. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 22 p. https://doi.org/10.2737/FPL-RP-711

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Contents

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Samuel V. Glass, Research Physical Scientist
C.R. Boardman, General Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

Prabu Ravindran, Assistant Scientist
Department of Botany, University of Wisconsin, Madison, Wisconsin, USA

Alex C. Wiedenhoeft, Research Botanist
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

1 Introduction

The U.S. wood flooring industry is an economically important segment of the larger forest products industry, accounting for over 2.4 billion USD and 960 million square feet of flooring in 2018 (Floor Covering News 2019). Among the main performance characteristics of wood flooring is dimensional movement with changes in moisture content. Understanding and quantifying movement is critical to the wood flooring industry, whether considering manufacturers' need for information for producing flooring and the development of installation guidance, installers' need to verify appropriate conditions for installation, or flooring inspectors' or homeowners' need to understand the behavior of an installed floor.

Although the shrinking and swelling of wood with moisture is addressed in many books on wood science and technology (for example, Stamm 1964, Kollmann and Côté 1968, Panshin and De Zeeuw 1970, Skaar 1988, Siau 1995, Hoadley 2000, Suchsland 2004, Shmulsky and Jones 2019), the U.S. wood flooring industry has relied on values and equations published by the Forest Products Laboratory (FPL) in its *Wood Handbook* to provide this critical information. For example, the installation guidelines published by the National Wood Flooring Association (NWFA) include example calculations of change in dimension with moisture content (NWFA 2007, 2019). The calculations make use of a dimensional change coefficient (DCC) and refer to other NWFA technical publications for a list of DCCs by species, and these technical publications (NWFA 1996, 2004, 2017) refer to the *Wood Handbook*. Similarly, a technical publication from the National Oak Flooring Manufacturers Association (NOFMA 2004) includes a list of DCCs from the *Wood Handbook*. In this introduction we summarize key information previously published by FPL relating to dimensional movement, describe the origin of the DCC, and discuss the motivation and objectives for the present study.

1.1 Historical Background on Wood Movement with Changes in Moisture Content

The primary way in which wood movement is reported is the green to ovendry shrinkage value, expressed as a percentage of the dimensions of the wood in the green condition. Shrinkage values are reported in the tangential direction (circumferentially around the tree), radially (from the center of the tree out toward the bark), longitudinally (along the length of the trunk), and volumetrically (the percentage change in total volume with no regard to the different directions). Shrinkage varies between and within species and in the three directions, with the greatest shrinkage in the tangential direction, the next greatest in the radial direction, and almost no shrinkage longitudinally.

The earliest FPL publication with shrinkage data appears to be *The Properties and Uses of Wood* (Koehler 1924). This book includes a table with volumetric, tangential, and radial green to ovendry shrinkage values for approximately 90 species. In addition, it has a figure in which volumetric shrinkage is plotted versus specific gravity for approximately 115 species.

Tables with volumetric, tangential, and radial green to ovendry shrinkage values have been published in the *Wood Handbook* since its first edition (FPL 1935). The data are most likely based on a technical bulletin by Markwardt and Wilson (1935) that lists shrinkage values for more than 150 species. This bulletin also provides information describing the measurement method. Notably, the shrinkage values were measured on small clear wood blocks with dimensions 25 by 25 by 100 mm (1 by 1 by 4 in.), oriented such that radial shrinkage was measured on blocks that were 100 mm

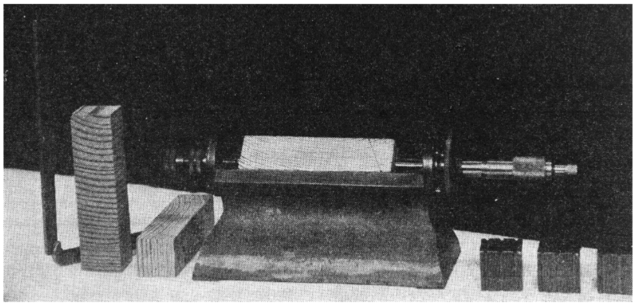

Figure 1—Reproduction of figure 37 from Markwardt and Wilson (1935) showing the testing apparatus used to determine green to ovendry shrinkage.

(4 in.) in the radial direction and tangential shrinkage was measured on blocks that were 100 mm (4 in.) in the tangential direction (Fig. 1).

The 1935 *Wood Handbook* includes a graph of shrinkage versus moisture content for Douglas-fir and southern yellow pine and indicates that it may be used for estimating the amount of change in dimension that will take place with change in moisture content of the wood, which is the earliest presage of the DCC.

Subsequent work by MacLean (1945) established an equation to estimate the total shrinkage of a board as a function of grain angle of the board based on the tangential and radial shrinkage values. That is, for any purely tangential (or radial) board, a tangential (radial) value would be fully applicable, but most boards have at least part of their width with some angle differing from purely tangential or radial. In this paper, we focus on tangential shrinkage because most commercial hardwood flooring is plainsawn and therefore presents primarily a tangential face, and thus flooring expansion and contraction are predominantly governed by wood properties in the tangential direction.

The topic of board-to-board shrinkage variation has been addressed in several reports. Markwardt and Wilson (1935) presented information on variability for many different wood properties using the range encompassing the middle 50% of the measured values (with 25% below this range and 25% above). Regarding radial and tangential shrinkage, the width of this range was about 20% of the mean value ($\mu \pm 0.1\mu$, where μ is the mean value). Peck (1947) presented several examples including a histogram showing variation in tangential green to ovendry shrinkage values for disparate boards of longleaf pine heartwood. Comstock (1965) published a seminal report with great detail on the shrinkage of Douglas-fir and redwood. The critical contributions of this report were the recognition that average values over many boards are important, and that by using such averages and statistical methods, useful predictions about wood shrinking or swelling could be made.

In addition to FPL's work on shrinkage and wood movement with changes in moisture content, other sources of data, especially for green to ovendry shrinkage, abound. Typically such references report shrinkage values species-by-species as one of many properties reported on technical information sheets (Chowdhury and Ghosh 1958, 1963; Farmer 1972; BRE 1977; Mainieri and Chimelo 1989; Sewell 1997; Fairbairn 1999; Flynn and Holder 2001; Flynn 2007; Ruffinatto and Crivellaro 2019), whereas other references (Bolza and Keating 1972, Keating and Bolza 1982) report shrinkage values for a great number of woods from around the world, but those values are grouped into categories rather than reported as specific values, so each wood is represented by a range.

1.2 Birth of the Dimensional Change Coefficient

The 1974 edition of the *Wood Handbook* (FPL 1974) is the first edition to include a table of DCCs. Although the *Wood Handbook* is clear that DCCs are based on green to ovendry shrinkage values, the method of deriving DCCs is not clearly stated. Nonetheless, the *Wood Handbook* makes several relevant points. It notes that a linear relationship between moisture content and shrinkage is assumed, and further, that shrinkage is assumed to start at 30% moisture content (MC) for all species except those indicated by footnote, for which shrinkage is assumed to start at 22% MC. We subsequently refer to this assumed value as the fiber saturation point (FSP). In addition, the *Wood Handbook* notes that DCCs are applicable within the moisture content limits of 6% to 14% and that DCCs are based on the dimension at 10% MC (the midpoint of the 6% to 14% MC range, rather than dimension at the green condition). The *Wood Handbook* gives the following equation for estimating change in dimension:

$$\Delta D = D_{\mathrm{I}} C_{\mathrm{T}} \left(M_{\mathrm{F}} - M_{\mathrm{I}} \right) \tag{1}$$

where ΔD is change in dimension (units of length), D_{I} is dimension (units of length) at start of change, C_{T} is dimensional change coefficient in the tangential direction, M_{F} is moisture content (%) at end of change, and M_{I} is moisture content (%) at start of change. The *Wood Handbook* gives another equation for approximate dimensional changes associated with moisture content changes outside the 6% to 14% MC range:

$$\Delta D = \frac{D_{\mathrm{I}} \left(M_{\mathrm{F}} - M_{\mathrm{I}} \right)}{30 \cdot 100 / S_{\mathrm{T}} - 30 + M_{\mathrm{I}}} \tag{2}$$

where S_{T} is tangential shrinkage (%) from green to ovendry (based on dimension at green condition). The number 30, which occurs twice in the denominator of this equation, is apparently the assumed FSP. Given these two equations and

Table 1—Correspondence between *Wood Handbook* DCC values and values calculated by Equation (3) using green to ovendry shrinkage (S_T) and assumed fiber saturation point

Species	Assumed FSP (%)	S_T (%)[a]	Calculated C_T	*Wood Handbook* C_T[b]
Ash, black	30	7.8	0.00274	0.00274
Cherry, black	30	7.1	0.00248	0.00248
Madrone, Pacific	30	12.4	0.00451	0.00451
Maple, sugar	30	9.9	0.00353	0.00353
White oak, live	30	9.5	0.00338	0.00338
Walnut, black	30	7.8	0.00274	0.00274
Cedar, western red	22	5.0	0.00234	0.00234
Douglas-fir, Coast	30	7.6	0.00267	0.00267
Hemlock, western	30	7.8	0.00274	0.00274
Pine, lodgepole	30	6.7	0.00234	0.00234
Redwood, old-growth	22	4.4	0.00205	0.00205
Spruce, black	30	6.8	0.00237	0.00237

[a] *Wood Handbook* table 4–3 (FPL 2010).
[b] *Wood Handbook* table 13–5 (FPL 2010).

the assumptions stated above, we derived the following equation for calculating the tangential DCC:

$$C_T = \frac{1}{\mathrm{FSP} \cdot 100 / S_T - \mathrm{FSP} + 10} \qquad (3)$$

Table 1 shows the application of this equation for 12 woods and the resultant correspondence with the *Wood Handbook* DCC values. This direct correspondence supports the notion that the *Wood Handbook* DCC values were originally calculated using this equation.

The 1999 edition of the *Wood Handbook* (FPL 1999) added a sentence noting that the dimensional change coefficient could be used to back-calculate initial moisture content of wood if the change in dimension was known and the current moisture content was known. The 1999 *Wood Handbook* was not the first publication to point this out. Jourdain and Dost (1987) demonstrated that a linear regression between measured board width and moisture content could be used, if the manufactured width was known, to accurately estimate the moisture content at the time of manufacture. Their method, however, required a unique linear regression for each individual board to achieve an accuracy within 1% MC because of the inherent board-to-board variability within a given species. Nonetheless, the DCC as an average value for a given species is based on the same principle as the linear regression between board width and moisture content.

The wood flooring industry has relied on DCC values from the *Wood Handbook* for years (as noted previously). However, FPL literature does not directly address

- specific analyses of the influence of natural variability on calculations based on DCCs;
- the relationship between movement in installed floorboards, uninstalled floorboards, and wood blocks with a rectilinear profile (laboratory test blocks); and
- a practical method to develop coefficients for species not included in published data.

1.3 Objectives

In this paper, we evaluate existing practices related to reporting, determining, and applying DCCs as they pertain to solid wood flooring. The intersection between basic wood properties and real-world practical considerations has driven our approach. This project was guided by the following objectives:

- Generate time-lapse videos of flooring assemblies clearly demonstrating movement with change in moisture content.
- Investigate the origins of the *Wood Handbook* DCC values for hickory and red oak in the context of expressing variability and reporting DCCs in a manner consistent with that uncertainty.
- Calculate DCC values for *Acacia confusa* and *Acacia mangium* based on any available data in the literature.
- Conduct experimental work to determine DCCs from floorboards of hickory, red oak, *Acacia* cf. *confusa*, and *Acacia* cf. *mangium*. This objective requires a number of sub-objectives:
  - Determine if the presence of finish on a board influences the equilibrium moisture content or calculation of wood specific gravity.
  - Determine DCCs of uninstalled floorboards and installed floorboards.
  - Compare DCCs of uninstalled and installed floorboards.
  - Compare experimentally determined DCCs to literature values.

  - Determine if the geometry of a board (tongue-and-groove profile or rectangular profile) influences the determination of DCC.
- Develop a practical method to determine DCCs for species not included in published data.
- Provide example calculations of moisture content at the time of manufacture, incorporating uncertainty in measured floorboard width, manufactured width, measured wood moisture content, and the value of the DCC itself.

Meeting these objectives required examining literature values and conducting experimental work.

2 Materials and Methods

2.1 Floorboards

Two boxes of prefinished commercial 3/4-in.- (19-mm-) thick solid wood flooring were acquired for each of four woods: hickory (*Carya* spp.), red oak (*Quercus* spp., red group), *Acacia* cf. *mangium,* and *Acacia* cf. *confusa*. Nominal floorboard widths were 3 in. (76.2 mm) for hickory and red oak, 90 mm for *Acacia* cf. *mangium*, and 92 mm for *Acacia* cf. *confusa*. We had no definitive evidence of species-level identification for any of these woods; we did not know which species (one or more) of hickory or red oak were in our boxes, nor did we have definitive identification of the species of *Acacia.* Given that, for the rest of this paper we refrain from using the italicized scientific names for the Acacia so that we do not present a false degree of taxonomic precision, but we use the word species throughout the paper to refer to the groups of woods, in keeping with convention in the flooring industry. Individual floorboards with grain angle predominantly plainsawn were selected for inclusion; quarter-sawn and less-tangential floorboards were excluded. Excluded boards were retained for use in gravimetric moisture content and specific gravity determination but were not included in dimensional change measurements. Widths of a selection of floorboards of each species were measured, giving rise to the measurements “as received” (Table 2).

For hickory and Acacia confusa, individual floorboards sometimes had both sapwood and heartwood. No effort was made to select floorboards that were bark-up or pith-up in any species. The *Wood Handbook* reports DCC values for the red oaks and for hickory, but neither the *Wood Handbook* nor any other reference reports DCC values for either Acacia.

2.2 Flooring Assemblies

2.2.1 Floorboard Remanufacture Prior to Installation

One intent of this study was to explore the uncertainty associated with calculating moisture content at the time of flooring manufacture or flooring installation. In our case, we restricted ourselves to moisture content at the time of manufacture. Industry standards for factory-finished solid wood flooring (NWFA 2018) specify that flooring is to be manufactured with moisture content between 6% and 10%, with an allowance for 5% of the pieces to be outside the 6% to 10% MC range. If manufactured at higher or lower moisture content than the standard, it must be stated on the packaging. Our experiment was meant to recreate a scenario in which floorboards were manufactured at a much higher moisture content than the industry standard, were installed at the same moisture content, and were then exposed to in-service conditions that resulted in a moisture content near 6%, resulting in noticeable gaps between floorboards. Inspection of the floor would involve measurement of floorboard widths and moisture contents. Knowledge of the DCC for the wood species and the width of the flooring specified by the manufacturer would allow for estimation of moisture content at the time of manufacture. Our experiment was meant to provide all the necessary measurements to estimate moisture content at the time of manufacture and to determine the reliability of such calculations by checking the calculated value against the actual measured moisture content at the time of manufacture. To accomplish this, we had to become the “manufacturer” by reconditioning the floorboards and remanufacturing them to new, known specifications. Boards were stickered in a conditioning room (80% RH) (Fig. 2). Board widths were measured and remanufactured at this condition. Based on the widths measured, we determined our target width for each wood for remanufacturing, such that the narrowest boards would still have some wood removed from them in the remanufacturing process.

We constructed a custom jig to allow us to use a 14-in. (356-mm) table saw to remove wood from the groove side of the board, referenced against the board width from the top contact face on the tongue side of the board (Fig. 3), with a routed slot for the tongue). We then determined the minimum width of tongue to remove from all boards to allow tight installation. The result was a target remanufactured board width, with a range of actual board widths. After remanufacturing, the boards were returned to the conditioning room, measured within 2 h of remanufacturing, and stored until installation on the subfloor assemblies. The width of each floorboard was measured to a precision of 0.01 mm using a digital caliper at two or three different locations that were indicated by a line across the finished surface with fluorescent marker, which allowed for measurement at the same locations after the floorboards were installed.

Data on remanufactured board widths for each of the four woods are plotted in Figure 4. The horizontal axis is individual board width, divided into ranges of widths, and the vertical axis is the proportion of the boards measured that fall into each size class. The blue curve in each graph is the proportion of boards within each width class as they came out of the boxes, with no reference to moisture content at time of measuring. This represents the ranges of widths that could have been present at a straight-from-the-box

Table 2—Pre- and post-remanufacturing measurements for floorboards of the four species

Condition	Number of boards measured	Total number of measure-ments	Mean width (mm)	Min width (mm)	Max width (mm)	Range (mm)	Target width (mm)	Percentage of measure-ments within tolerance of target width
Hickory								
1. As received	14	42	76.43	76.09	76.62	0.53	N/A	N/A
2. Equilibrium at 80% RH	33	76	78.38	77.73	79.42	1.69	N/A	N/A
3. After remanufacturing	33	76	77.31	76.25	77.84	1.59	77.3	64
Red oak								
1. As received	8	24	76.44	75.97	76.76	0.79	N/A	N/A
2. Equilibrium at 80% RH	33	77	77.68	76.98	78.49	1.51	N/A	N/A
3. After remanufacturing	33	77	76.64	75.58	77.11	1.53	76.6	68
Acacia confusa								
1. As received	12	36	91.98	91.35	92.28	0.93	N/A	N/A
2. Equilibrium at 80% RH	38	76	92.91	91.63	93.77	2.14	N/A	N/A
3. After remanufacturing	38	76	91.23	90.63	91.94	1.31	91.2	55
Acacia mangium								
1. As received	14	42	89.49	89.26	89.70	0.44	N/A	N/A
2. Equilibrium at 80% RH	32	70	90.21	89.94	90.72	0.78	N/A	N/A
3. After remanufacturing	32	70	89.47	89.07	89.86	0.79	89.5	77

Figure 2—Image of stickered floorboards in 80% RH conditioning room.

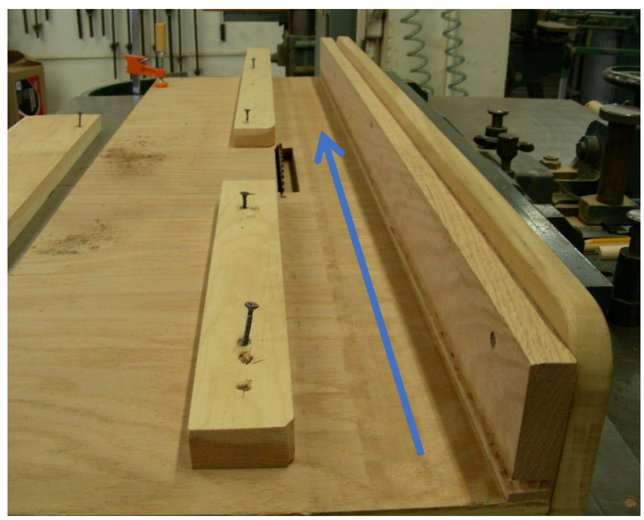

Figure 3—Image of the table saw remanufacturing jig in the groove-side configuration. The blue arrow denotes the travel of the specimen. Safety cover over blade removed to show position of blade.

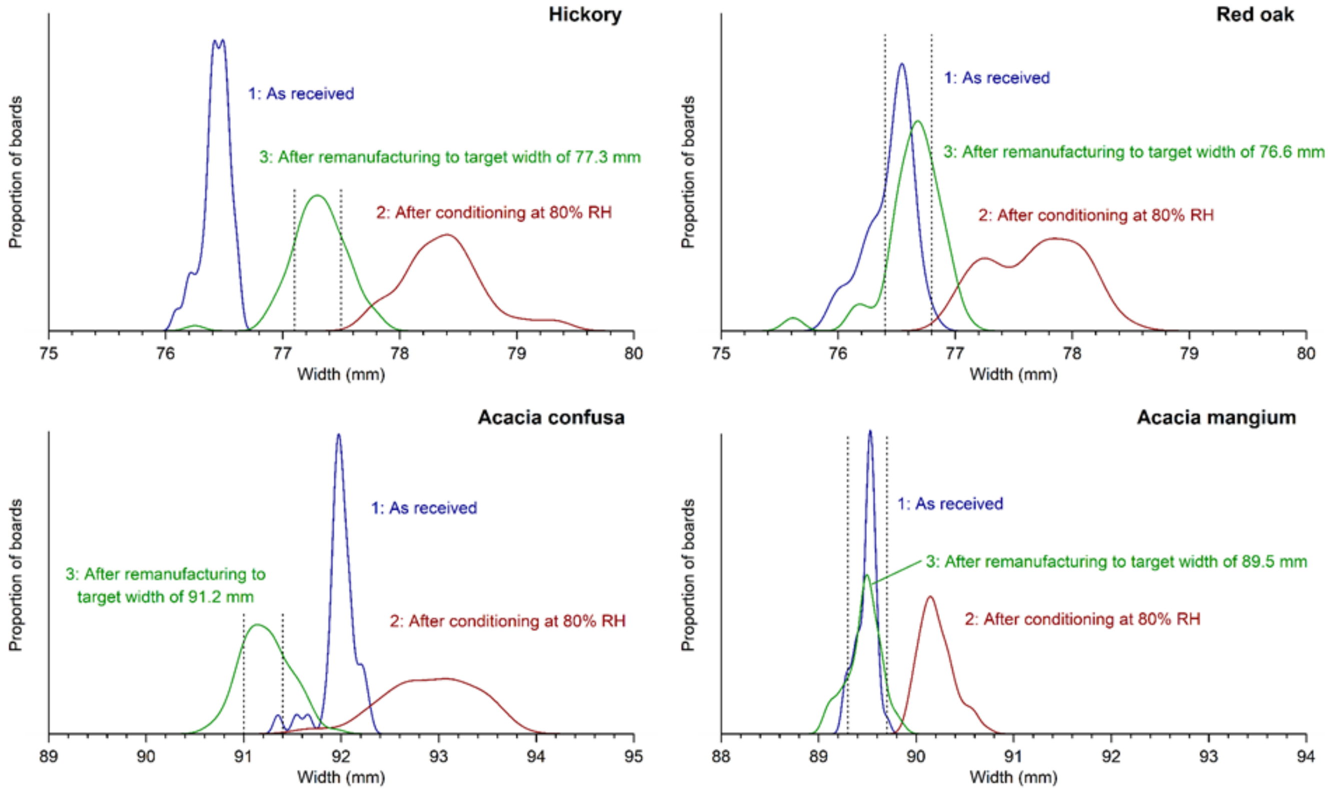

Figure 4—Proportion of floorboards having a given width as received (blue), after conditioning to equilibrium at 80% RH (red), and after remanufacturing at 80% RH (green). NWFA/NOFMA manufacturing tolerances (NWFA 2018) are reported as vertical dashed lines: ±0.008 in. (0.20 mm) either side of the target width.

installation. The red curve is the proportion of those same boards after conditioning at 80% RH. The green curve is the proportion of boards in each size class after remanufacturing at FPL to a specified width. The vertical dotted lines represent the target width range based on NWFA/NOFMA manufacturing tolerances for factory-finished solid wood planks (NWFA 2018). Tolerances are expressed as a given width plus or minus 0.008 in. (0.20 mm).

Data used to generate Figure 4 are summarized in Table 2 for completeness. Some percentage of width measurements on the remanufactured boards were outside NWFA/NOFMA tolerances. We selected the boards closest to the target dimensions for installation in the assemblies.

2.2.2 Subfloor Assemblies and Floorboard Installation

Four subfloor assemblies were constructed using 23/32 in. (18 mm) Sturd-I-Floor plywood glued and screwed to a frame constructed from nominal 2- by 4-in. (standard 38- by 89-mm) lumber in which “joists” were spaced 16 in. (406 mm) on center. The subfloor dimensions were 48 by 65.5 in. (1.22 by 1.66 m) with “joists” running parallel to the 48-in. (1.22-m) dimension. Selected, conditioned, and remanufactured floorboards were installed onto the subfloor assemblies over an underlayment by a NWFA-certified flooring installer and according to NWFA installation standards to the extent possible. Cleats were used to fasten hickory and both Acacia. Staples were used to fasten red oak.

2.2.3 Conditioning and Imaging Space

A temporary conditioning space for all four flooring assemblies was created within laboratory space maintained near 50% RH and between 23 and 29 °C. This space was used to expose the flooring assemblies to a nominal 80% RH condition and a nominal 30% RH condition. The space had a footprint of 4.9 by 4.9 m and a ceiling height of 3.5 m. Polyethylene sheet (0.15 mm) was stapled to the sides of wood framing and overlaps were sealed with tape. The walls and ceiling were covered on the interior by crinkled white polyolefin house wrap to improve diffuse lighting for time-lapse photography. The final assembly also had a large resealable opening on one side to allow entry. Figure 5 shows the nearly completed assembly.

The temperature in the conditioning space fluctuated with the laboratory space temperature, between 23 and 29 °C. Humidity to raise the space to over 80% RH was supplied by a steam humidifier controlled by a wall-mount humidistat, which was supplied with water via gravity from a plastic tank through a float valve. Room humidity was generally maintained in a band between 83% and 90% RH, with an average of 86%, as monitored by a RH and

Figure 5—Image of the exterior of the conditioning space with the "door" partly open. This image was prior to installing the flooring assemblies and imaging and lighting hardware.

temperature data logger (HOBO UX100-011, Onset Computer Corp., Bourne, Massachusetts) accurate to ±2.5% RH mounted near the flooring assemblies. Uniformity of humidity within the room was maintained by small room fans continuously circulating air inside the space.

The 30% RH condition was attained (with humidifier turned off) using a dehumidifier (Santa Fe Advance, Therma-Stor LLC, Madison, Wisconsin) controlled by an internal dehumidistat. Measured conditions varied between 23% and 33% RH, with an average of 28%, as monitored by the same RH and temperature data logger. Condensate from the dehumidifier ran to a drain in the floor.

2.2.4 Time-Lapse Imaging

Four Canon SX280HS digital cameras (Canon, Inc., Tokyo, Japan), one for each flooring assembly, were programmed to take images of the installed boards at three different zoom levels once each day. The camera imaging parameters were manually fixed at f/8, ISO-100, and 1 s exposures. The supplied rechargeable batteries were replaced with AC adapters to handle the power consumption requirements of the cameras.

Camera mounts were designed to allow each camera to be centered over the middle of the flooring assembly and as parallel to the floor as possible. A rigid three-dimensional frame was created from 38-mm aluminum T-slot framing for each flooring assembly. The flooring assemblies were mounted to the bottom rails, which had wheels to allow easy movement of the assemblies into the conditioning space (Fig. 6, top). The upper section of the box had a custom

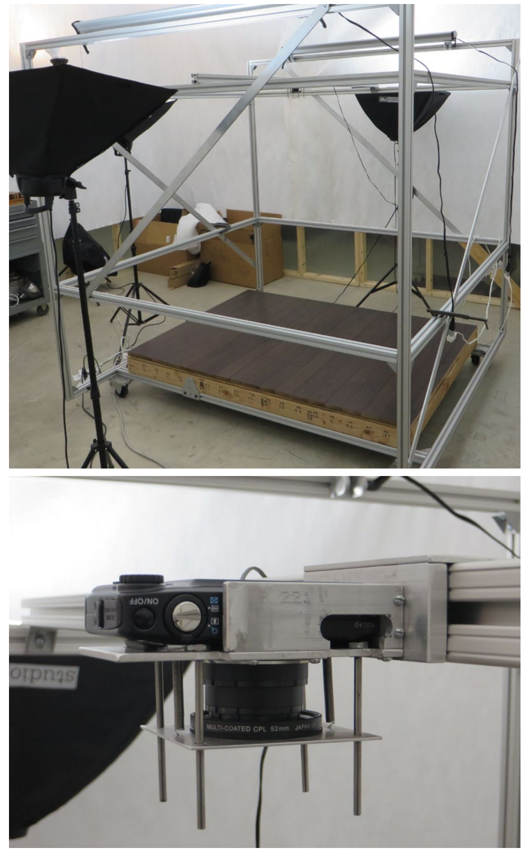

Figure 6—Top: image of the aluminum frame and the Acacia mangium flooring assembly. Bottom: camera mount system allows use of a polarizing filter at the various zoom levels.

camera mount that could slide on a rail to adjust position and be locked down once centered (Fig. 6, bottom).

Fovitec Studio Pro series (Fovitek, Irvine, California) 20- by 28-in. rectangular softbox lighting kits with compact fluorescent bulbs were directed at the crinkled off-white polyolefin-covered ceiling and walls to achieve even, diffuse illumination. Glare off the flooring assemblies was reduced by use of a polarizing filter affixed to the camera mount.

For each flooring assembly, a metal ruler was placed on one of the floorboards (approximately parallel to and away from the board's edges) to provide a within-image scale bar for visualization and to serve as an image registration template for the creation of reduced-jitter, time-lapse videos to demonstrate the shrinking and swelling of the flooring assemblies.

2.2.5 Compiling Time-Lapse Videos of Flooring Assemblies

Images of each floor assembly at three different zoom levels were captured daily over three months as the flooring assemblies adjusted to a change in humidity from over 80%

to below 30%, and then again from below 30% to over 80%. We post-processed the ("jumpy") raw time-lapse image sequences using template matching (Szeliski 2010), a standard computer vision technique implemented in the OpenCV library (Bradski 2000), to compile smoother videos that enabled clear visualization of the shrinking and swelling of boards in the flooring assemblies. In the first image of each image sequence, we manually marked the image patch that contained the metal ruler to serve as the template. The affine transformation that best localizes the template patch in a target image is estimated by sweeping the template patch over the (transformed) target image and measuring the quality of alignment using the cross-correlation metric. At the end of the template matching procedure, the template patches in all the images of a sequence are registered (that is, they have the same position, orientation, and scale). The template-matched images for each assembly at each zoom level were then compiled in ImageJ software (Schneider et al. 2012) into a video. The template matching procedure greatly reduced the amount of jitter in the time lapse videos and provided a clear visual demonstration of shrinkage and swelling in the installed floorboards.

2.2.6 Measuring Width of Installed Floorboards

After the flooring assemblies had equilibrated at the nominal 30% RH condition, the width of each installed floorboard was measured to a precision of 0.01 mm using a digital caliper, at the same locations as prior to installation (as indicated by a line across the finished surface with fluorescent marker; see Section 2.2.1). To facilitate caliper measurements, a thin steel plate was attached to each arm of the caliper such that the plates could be inserted into the gaps between floorboards to make contact with the groove side and the top contact face on the tongue side.

2.3 Uninstalled Floorboards

2.3.1 Floorboard Conditioning to Achieve Equilibrium Moisture Content

Floorboards were stored in various conditioning spaces that controlled, with various degrees of precision, the RH and temperature of the space. The sequence of conditions was nominally 80% RH at 27 °C; 65% RH at 27 °C; 50% RH at 22 °C; 30% RH at 27 °C; 50% RH at 22 °C; and 65% RH at 27 °C. Temperature and RH were monitored at 15-min intervals using data loggers. Actual RH conditions were in some cases slightly different from nominal conditions. To determine that the floorboards reached equilibrium moisture content (EMC) at each condition, boards were conditioned at least two months, and the mass of a subsample of boards was measured weekly until consecutive mass readings differed by less than 0.05%. After reaching equilibrium at a given condition, specimens were weighed with an electronic balance to 0.01 g.

Specimens were ovendried after the sequence of moisture conditions in a convection oven set to 105 °C (±1 °C) for a minimum of 48 h. Specimens were considered dry when consecutive weighings 24 h apart differed by less than 0.1%.

Figure 7—Photograph of the two specimen profiles in each of the four species. The high density of Acacia confusa coupled with its dark heartwood color yielded a scorched surface in board Co55a, making the label difficult to discern in this image.

2.3.2 Effect of Surface Finish on EMC and Specific Gravity

To ensure that the surface finish did not influence subsequent calculation of DCCs, we cut 10 specimens from floorboards rejected for nontangential grain angle from each species of prefinished flooring. Each specimen was cut to a rectangular profile to facilitate volume calculation (~64 mm wide with tongue-and-groove entirely removed, ~250 mm along the grain, and 16.5 mm thick). Each specimen was then cut in half to give two matched subgroups. The surface finish was planed off the boards of one subgroup and left intact in the other. Both groups were conditioned to equilibrium at 23 °C and 50% RH. Specimens were weighed and dimensions measured (to a precision of 0.01 mm using a digital caliper), then ovendried, weighed, and measured again to determine specific gravity and whether including the finish introduces any appreciable error into gravimetric moisture content measurement.

2.3.3 Effect of Board Profile on DCC

Ten floorboards were selected from each species and were initially sawn to 300 mm in length. After conditioning to equilibrium at 80% RH, each floorboard was sawn into a pair of 150-mm matched specimens. The original tongue-and-groove profile (board marked a) was retained for one specimen of each matched pair, and the other specimen was sawn to a rectangular profile (boards marked b) (Fig. 7). These specimens are referred to hereafter as "rectangular cuboid" specimens. Although great care was taken to plane these short specimens, several of the hickory and red oak specimens were damaged in the process and had to be excluded. A line across the width of the face of each specimen was drawn through the center (75 mm from each end). Width across the center line of each specimen was measured to a precision of 0.01 mm using a digital caliper. For rectangular cuboid specimens, the width was also measured near each end; thickness was measured near each end and at the center; and length was measured at the center.

Volume was calculated based on length, average width, and average thickness.

2.4 Determination of Grain Angle

The proportion of board width presenting a grain angle within 20° of tangential was measured for a sample of 10 boards of each species for both tongue-and-groove and rectangular cuboid board profiles. One transverse surface of each specimen was cut with a sharp utility knife to permit determination of the angle of rays with respect to the upper surface of the board. This was facilitated by placing a glass microscope slide marked with 70° lines relative to the long edge of the slide and passing this slide laterally until the ray angle was matched. The corresponding position was marked on the top surface of the board. Most boards acquired two marks as the grain angle transitioned across the boards. The distance between the marks was measured with a caliper micrometer, rounded to the nearest millimeter, and divided by the board-top width, also measured to the nearest millimeter with a caliper micrometer.

2.5 Moisture Meter Measurements

Measurements were taken on installed floorboards using a handheld pinless moisture meter (Wagner Meters, Model MMC 220, Rogue River, Oregon). The specific gravity (SG) setting on the meter for each species group was selected based on initial SG measurements described in Section 2.3.2. Mean SG values were 0.80 (hickory), 0.68 (red oak), 0.73 (Acacia confusa), and 0.50 (Acacia mangium).

The accuracy of the moisture meter was investigated by acquiring meter readings for all uninstalled floorboard specimens at each EMC condition (Section 2.3.1). It is well known that individual moisture meter readings vary significantly between boards of the same species at the same EMC condition (Wengert and Bois 1997, Wilson 1999). In our measurements, individual readings were in some cases more than 3% MC above or below the mean value for specimens of the same wood at the same EMC. However, variation of individual readings was not considered further because mean values were used in all subsequent analysis. The mean moisture content of each species group based on meter readings was plotted against the mean gravimetric EMC (based on mass measurements at each RH condition and the ovendry condition). Data for each species group were fit with a linear regression; the coefficient of determination (R^2) ranged from 0.96 to 0.99. The absolute differences between the mean EMC values measured gravimetrically and the regression line (based on mean meter readings) were less than 0.7% MC for Acacia confusa, less than 0.6% for hickory, less than 0.5% for Acacia mangium, and less than 0.4% for red oak. The linear regressions were subsequently used for correcting the mean values of meter readings on each group of installed floorboards.

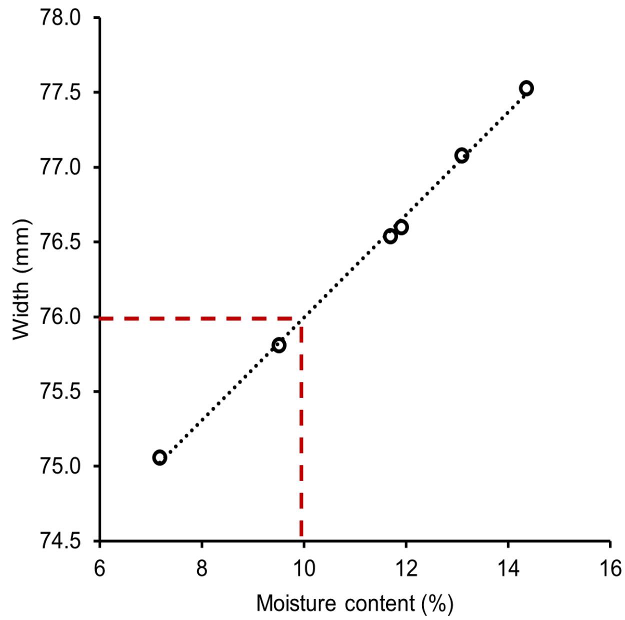

Figure 8—Width of a 150-mm-long hickory floorboard at different equilibrium moisture contents. Circles indicate measured values. The black dotted line is the regression line. The red dashed lines show the interpolated reference width at 10% MC.

2.6 Determination of DCCs from Floorboards

Dimensional change coefficients were determined for uninstalled floorboards using two different methods. The first method used a linear regression of the measured widths versus the measured EMCs at each condition. An example for hickory is shown in Figure 8. The regression line is the black dotted line. The slope of this line indicates how much the floorboard width changed for a change in moisture content. The red dashed line indicates the reference width at 10% MC, which was found by interpolation using the regression line. The DCC was calculated as the slope of the regression line divided by the reference width at 10% MC. (The reference width at 10% MC has its origin in the way the DCC is defined; see Section 1.2.)

The second method for calculating DCCs used a pair of measurements under two different conditions:

$$C_{exp} = \frac{D_1 - D_2}{D_{ref}\left(M_1 - M_2\right)} \tag{4}$$

where C_{exp} is the experimentally determined DCC, D_1 and D_2 are measured widths at equilibrium moisture contents M_1 and M_2, respectively, and D_{ref} is the reference width at 10% MC determined from the linear regression mentioned above. DCCs for uninstalled boards were calculated using a series of two conditions, which are labeled below with the nominal RH level (where "s" indicates sorption from a lower previous moisture condition and “d” indicates desorption from a higher previous moisture condition):

- EMC80(s) to EMC65(d)
- EMC65(d) to EMC50(d)
- EMC50(d) to EMC30(d)
- EMC30(d) to EMC50(s)
- EMC50(s) to EMC65(s)
- Each of the above conditions to ovendry
- EMC80(s) to EMC30(d)

In addition, averages were taken for the DCCs corresponding to desorption steps, DCCs corresponding to sorption steps, and DCCs corresponding to each condition to ovendry. This allowed us to examine the effects, if any, of sorption hysteresis on the calculation of DCCs. DCCs for installed floorboards were calculated using the EMC80(s) to EMC30(d) method described above.

2.7 Calculation of DCCs from Literature Shrinkage Values

DCCs for Acacia mangium were calculated using Equation (3) based on shrinkage values from TROPIX 7 (CIRAD 2012), Chowdhury et al. (2005), and the Wood Database (https://www.wood-database.com/mangium/), and for Acacia confusa based on values from a commercial information sheet (Horeca International Ltd. [no date]). FSP for Acacia mangium was taken as 25% MC based on CIRAD (2012). FSP for Acacia confusa was not found in any references, and the DCC was calculated assuming FSP values of 22%, 25%, and 30% MC.

2.8 Statistical Inference

Statistical analysis was conducted in Excel (Microsoft, Redmond, Washington). Calculated statistics for groups of values included mean, standard deviation, and coefficient of variation (COV). We also calculated the 95% confidence interval for DCC values. Comparisons between treatments were conducted with the Student’s *t*-test, either paired or unpaired based on the specific treatments. We chose $p < 0.05$ as the threshold for significance. We frequently note that statistical significance does not necessarily connote a meaningful difference in the practical application of DCCs to flooring.

2.9 Propagation of Measurement Uncertainty

All measurements contain some degree of inaccuracy or uncertainty. For example, a width measurement expressed as 75.5 mm ± 0.2 mm indicates that the actual width is between 75.3 mm and 75.7 mm. The value “± 0.2 mm” is called the measurement uncertainty, which is half the range. We consider the effects of measurement uncertainty on two types of calculations. First, when the DCC for installed floorboards is calculated using Equation (4), the value depends on measured moisture contents (M_1 and M_2), measured board widths (D_1 and D_2), and a reference width (D_{ref}) calculated from the measured values. The uncertainty in the DCC value is calculated based on propagation of uncertainty in the measured quantities. These uncertainties are denoted $u(x_i)$ where x_i is the relevant quantity; for example, the uncertainty in moisture content at the start is denoted $u(M_1)$. Based on the general method of uncertainty propagation (Coleman and Steele 2018), the uncertainty in the experimental DCC value can be expressed as

$$u\left(C_{exp}\right)^2 = \left(\frac{\partial C_{exp}}{\partial D_1}\right)^2 u\left(D_1\right)^2 + \left(\frac{\partial C_{exp}}{\partial D_2}\right)^2 u\left(D_2\right)^2 + \left(\frac{\partial C_{exp}}{\partial D_{ref}}\right)^2 u\left(D_{ref}\right)^2 + \left(\frac{\partial C_{exp}}{\partial M_1}\right)^2 u\left(M_1\right)^2 + \left(\frac{\partial C_{exp}}{\partial M_2}\right)^2 u\left(M_2\right)^2 \quad (5)$$

After evaluating the partial derivatives, this equation can be simplified to

$$\frac{u\left(C_{exp}\right)}{C_{exp}} = \left[\frac{u\left(D_1\right)^2 + u\left(D_2\right)^2}{\left(D_1 - D_2\right)^2} + \frac{u\left(D_{ref}\right)^2}{D_{ref}^2} + \frac{u\left(M_1\right)^2 + u\left(M_2\right)^2}{\left(M_1 - M_2\right)^2}\right]^{1/2} \quad (6)$$

The second type of calculation is the moisture content at the time of manufacture, M_I (%), which can be calculated based on current moisture content, M_F (%), current floorboard width, D_F (mm), dimensional change coefficient, C_T, and the known width at the time of manufacture, D_I (mm), as

$$M_I = M_F - \frac{D_F - D_I}{C_T D_I} \quad (7)$$

The uncertainty in the calculated value of M_I depends on the measurement uncertainties in M_F and D_F, the estimated variability in C_T, and the manufacturing tolerance in D_I. Propagation of uncertainties in the same manner as Equation (5) yields the uncertainty in moisture content at time of manufacture as

$$u\left(M_I\right) = \left[u\left(M_F\right)^2 + \left(\frac{D_F}{C_T D_I^2}\right)^2 u\left(D_I\right)^2 + \left(\frac{1}{C_T D_I}\right)^2 u\left(D_F\right)^2 + \left(\frac{D_F}{C_T^2 D_I} - \frac{1}{C_T^2}\right)^2 u\left(C_T\right)^2\right]^{1/2} \quad (8)$$

3 Results and Discussion

3.1 Time-Lapse Videos of Shrinkage and Swelling in Flooring Assemblies

We present time-lapse videos (Appendix) for each wood type, showing a close-up view of just a few boards, and one at a lower magnification showing wood shrinkage and swelling across several boards, clearly demonstrating movement with changes in moisture content. The flooring assemblies were conditioned to 80% RH and imaged as they were allowed to dry to 30% RH, and then imaged again as the assemblies were driven back to 80% RH.

3.2 Evaluation of DCCs for Red Oak and Hickory in the Wood Handbook

Dimensional change coefficients for various wood species are listed in table 13–5 of the 2010 edition of the *Wood Handbook* (FPL 2010). The DCC values and shrinkage from green to ovendry for hickory and red oak are examined here.

Four species of true hickory are listed in table 4–3 of the 2010 *Wood Handbook*. The shrinkage values are reproduced in Table 3, along with calculated DCC values using Equation (3). The average tangential shrinkage for these four species of 11.4% gives a calculated tangential DCC of 0.00411, which is identical to the value listed in table 13–5 of the 2010 *Wood Handbook*. This lends support to the notion that the values in the *Wood Handbook* were originally calculated using Equation (3). More importantly, Table 3 clearly shows that variation between species is appreciable. The precision of the DCC values reported in the *Wood Handbook* (five decimal places, or three significant figures) is clearly not meaningful given the behind-the-scenes variation from 0.00376 to 0.00459.

Table 13–5 of the 2010 *Wood Handbook* lists several entries for red oak: “Red Oak, commercial,” “Red oak, California,” and “Red oak: water, laurel, willow.” A reasonable inference is that the commercial group comprises the red oak species listed in table 4–3 of the *Wood Handbook* that are not California red oak, water, laurel, or willow oak. The remaining five species are listed in Table 4. The average tangential shrinkage for these five species of 10.3% gives a calculated tangential DCC of 0.00369. Again, this is identical to the value listed in table 13–5 of the *Wood Handbook*, and again, the variation between species is appreciable, with values ranging from 0.00304 to 0.00407.

In addition to the variability within the above-mentioned true hickory group and commercial red oak group, chapter 4 of the *Wood Handbook* states that shrinkage variability for a particular species can be characterized by a coefficient of variation of approximately 15%.

Given the range of single-species DCCs within both the hickory group value and red oak group value reported in the *Wood Handbook*, a single DCC may not adequately represent the DCC for a commercial group of woods. Additionally, when looking at Equation (3), the input FSP values are accurate to only two significant figures, which means that the final reported DCC value should be no more accurate than two significant figures. For these reasons together, we recommend that DCCs be reported only to two significant figures hereafter. The average DCC value for hickory in Table 3 would become 0.0041, and that of red oak from Table 4 would become 0.0037. This convention is followed hereafter in this paper.

Table 3—Details of the species imputed to generate the single DCC value reported in the *Wood Handbook* for hickory

Species	Tangential shrinkage (%) from green to ovendry moisture content	DCC calculated using Equation (3)
Hickory, true (group)		
Mockernut	11.0	0.00396
Pignut	11.5	0.00415
Shagbark	10.5	0.00376
Shellbark	12.6	0.00459
Average (group)	11.4	0.00411

Table 4—Details of the species imputed to generate the single DCC value reported in the *Wood Handbook* for red oak

Species	Tangential shrinkage (%) from green to ovendry moisture content	DCC calculated using Equation (3)
Oak, red (group)		
Black	11.1	0.00400
Northern red	8.6	0.00304
Pin	9.5	0.00338
Scarlet	10.8	0.00388
Southern red	11.3	0.00407
Average (group)	10.3	0.00369

3.3 Calculated DCCs for Acacia mangium and Acacia confusa Based on Literature Values

Table 5 presents tangential DCCs for the two Acacia species calculated using Equation (3), based on previously reported literature values for green to ovendry shrinkage and reported (Acacia mangium) or assumed (Acacia confusa) FSP.

3.4 Experimentally Determined DCCs from Floorboards

Historically, wood shrinkage was measured from unfinished, green, uninstalled, rectangular cuboid specimens (Markwardt and Wilson 1935; see Section 1.1). Floorboards are finished, dry, installed, tongue-and-groove pieces of wood. We sought to determine whether these factors affect wood behavior in response to changes in RH, or otherwise alter baseline wood properties.

Table 5—Calculated DCC values for the two Acacia based on FSP and total tangential shrinkage values available or assumed from the literature

Species	Source	FSP (%)	Shrinkage (%)	DCC
Acacia confusa	Horeca International Ltd. [no date]	22[a]	7.0	0.0033
		25[a]	7.0	0.0029
		30[a]	7.0	0.0025
Acacia mangium	CIRAD (2012)	25	7.0	0.0029
	Chowdhury et al. (2005)	25[b]	6.0–7.1	0.0025–0.0030
	www.wood-database.com/mangium/	25[b]	7.8	0.0033

[a] Assumed (no information).
[b] Assumed based on value reported by CIRAD (2012).

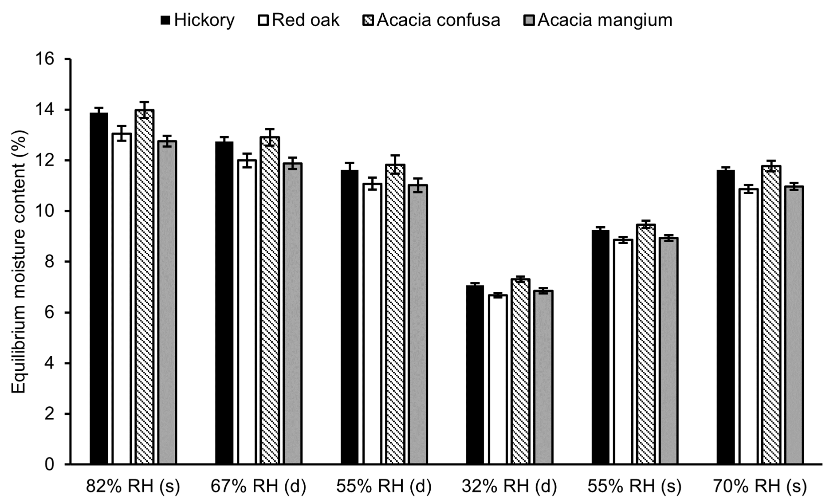

Figure 9—Equilibrium moisture content of uninstalled floorboards under sequence of relative humidity conditions (s, sorption; d, desorption). Error bars represent 95% confidence intervals.

Table 6—EMC data for installed floorboards

Species	EMC80(s) (%)[a]	EMC30(d) (%)[b]
Hickory	13.9 ± 0.3	6.6 ± 0.6
Red oak	12.9 ± 0.3	6.0 ± 0.4
Acacia confusa	14.0 ± 0.3	7.5 ± 0.7
Acacia mangium	12.6 ± 0.3	6.4 ± 0.5

[a] Based on gravimetric measurements on uninstalled floorboards in the same conditioning room as installed floorboards prior to installation; s, sorption.
[b] Based on corrected moisture meter readings on installed floorboards; d, desorption.

3.4.1 EMC of Uninstalled and Installed Floorboards

To establish DCCs based on either uninstalled or installed floorboards, we first had to determine the actual moisture content of the floorboards at each RH condition. Data on EMC at various RH conditions for installed floorboards are presented in Table 6, and a graphical summary of similar data for the uninstalled floorboards is shown in Figure 9.

3.4.2 Effect of Surface Finish on EMC and SG

The influence of factory-applied surface finish on EMC and SG is presented in Table 7. Because the surface finish is assumed to retard moisture transfer through the coated surface and because the mass of the finish would be included in a calculated wood density despite being nonwood material, we measured the effect of the presence or absence of a surface finish on each of these parameters. Only for red oak and Acacia mangium EMC do we find statistically significant differences between uncoated and finished wood, but the small difference of 0.15% is not of practical concern because larger issues of sorption hysteresis, individual board variability, and moisture meter error easily swamp the difference.

3.4.3 DCCs for Uninstalled Floorboards

Dimensional change coefficients are reported for uninstalled tongue-and-groove floorboards in Table 8, using the calculation methods described previously. The 95% confidence interval primarily reflects specimen-to-specimen

Table 7—Influence of finish on equilibrium moisture content and specific gravity[a]

Species	Number of matched specimens	Equilibrium moisture content: Mean difference (% MC)	Equilibrium moisture content: *p*-value	Specific gravity: Mean difference	Specific gravity: *p*-value
Hickory	10	0.12	0.10	0.002	0.42
Red oak	9	**0.15**	**0.0002**	–0.002	0.85
Acacia confusa	5	0.05	0.35	–0.002	0.87
Acacia mangium	7	**0.15**	**0.017**	–0.005	0.48

[a] Statistical results are from paired *t*-tests for matched rectangular cuboid specimens cut from commercial prefinished flooring with finish removed versus finish retained. Bold values are statistically significant at $p < 0.05$.

Table 8—Dimensional change coefficients for uninstalled floorboards[a]

Initial–final condition	Hickory	Red oak	Acacia confusa	Acacia mangium
EMC80(s)–EMC65(d)	0.0045 ± 0.0006	0.0056 ± 0.0005	0.0047 ± 0.0005	0.0032 ± 0.0006
EMC65(d)–EMC50(d)	0.0049 ± 0.0006	0.0023 ± 0.0001	0.0032 ± 0.0004	0.0034 ± 0.0006
EMC50(d)–EMC30(d)	0.0036 ± 0.0003	0.0037 ± 0.0002	0.0027 ± 0.0006	0.0022 ± 0.0003
Mean desorption	0.0043 ± 0.0003	0.0039 ± 0.0005	0.0035 ± 0.0005	0.0030 ± 0.0003
EMC30(d)–EMC50(s)	0.0041 ± 0.0002	0.0042 ± 0.0005	0.0032 ± 0.0003	0.0031 ± 0.0003
EMC50(s)–EMC65(s)	0.0038 ± 0.0004	0.0033 ± 0.0002	0.0028 ± 0.0007	0.0024 ± 0.0003
Mean sorption	0.0039 ± 0.0002	0.0038 ± 0.0003	0.0030 ± 0.0005	0.0028 ± 0.0002
EMC80(s)–OD	0.0036 ± 0.0002	0.0028 ± 0.0003	0.0028 ± 0.0005	0.0026 ± 0.0002
EMC65(d)–OD	0.0035 ± 0.0003	0.0026 ± 0.0004	0.0026 ± 0.0005	0.0025 ± 0.0002
EMC50(d)–OD	0.0033 ± 0.0003	0.0026 ± 0.0004	0.0025 ± 0.0005	0.0024 ± 0.0002
EMC30(d)–OD	0.0032 ± 0.0003	0.0018 ± 0.0007	0.0024 ± 0.0005	0.0026 ± 0.0002
EMC50(s)–OD	0.0034 ± 0.0003	0.0024 ± 0.0005	0.0026 ± 0.0004	0.0027 ± 0.0002
EMC65(s)–OD	0.0035 ± 0.0002	0.0026 ± 0.0004	0.0027 ± 0.0005	0.0026 ± 0.0002
Mean EMC–OD	0.0034 ± 0.0003	0.0025 ± 0.0004	0.0026 ± 0.0005	0.0026 ± 0.0002
EMC80(s)–EMC30(d)	0.0039 ± 0.0003	0.0038 ± 0.0002	0.0031 ± 0.0005	0.0026 ± 0.0003
Regression	0.0038 ± 0.0003	0.0036 ± 0.0002	0.0029 ± 0.0006	0.0024 ± 0.0003

[a] Mean value with 95% confidence interval. s, sorption; d, desorption; OD, overdry.

variation in DCC. Additionally, in some instances it may reflect random error in measurements. For example, DCCs calculated from EMC values that are closely spaced have a higher relative error than DCCs calculated from EMC values spaced farther apart.

The regression calculation method (Fig. 10) takes into account all the measured EMCs and widths between about 6% to 7% EMC (30% RH) and 13% to 14% EMC (80% RH) and thus represents the best value for each species. Select DCC values calculated using the two-condition method are compared with regression DCC values in Figure 11. The values calculated with the EMC80(s)–EMC30(d) method are generally close to the regression values and in all cases slightly higher, though the difference is 8% or less and consistently within the 95% confidence interval. For the Acacia, the DCC values calculated from different EMC values to the ovendry condition are close to the regression DCC value and within the 95% confidence interval. For hickory, the ovendry DCC values are lower than the regression DCC values by 0.0002 to 0.0006. The DCC values for red oak based on the ovendry condition are clearly much lower than the regression DCC value.

The DCC calculation method using one EMC condition and the ovendry condition was examined because in practice this method would save time and effort when determining DCC values for species not included in published data. However, the analysis of Figure 11 indicates that this method is questionable, at least when applied to commercial hickory and red oak floorboards. Furthermore, we found that a considerable number of specimens upon ovendrying exhibited cupping or crowning, thus making the ovendry width measurement unreliable. Practical methods for determining DCC values of species not included in published data are further discussed in Section 3.7.

3.4.4 Influence of Floorboard Profile on DCCs

Table 9 summarizes data comparing DCCs determined from tongue-and-groove and rectangular cuboid specimens to determine if there are statistically significant and/or practically important differences in measured DCCs

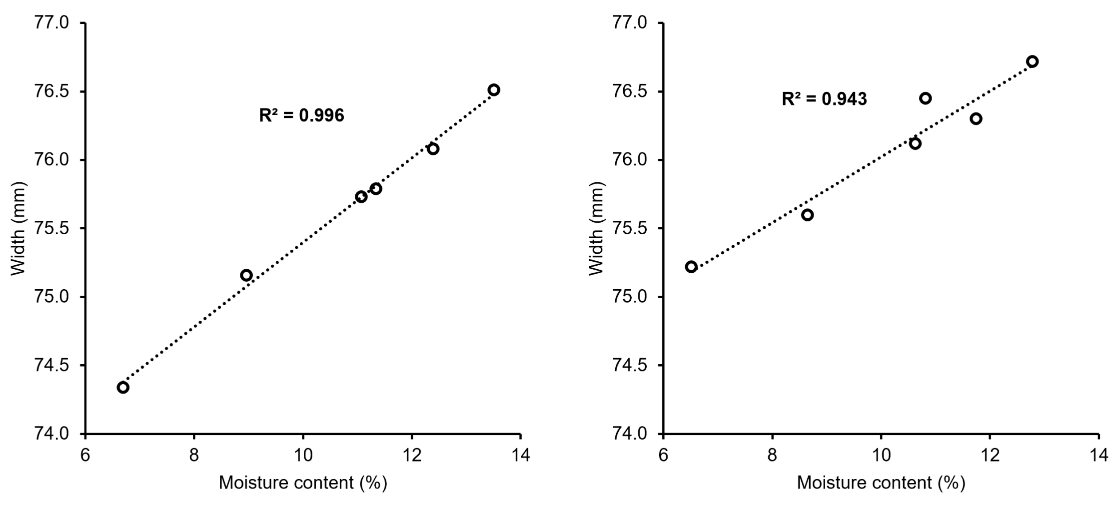

Figure 10—Two examples of regressions of width on moisture content for red oak uninstalled floorboards to show well-behaved experimental data (left) and less linear data (right).

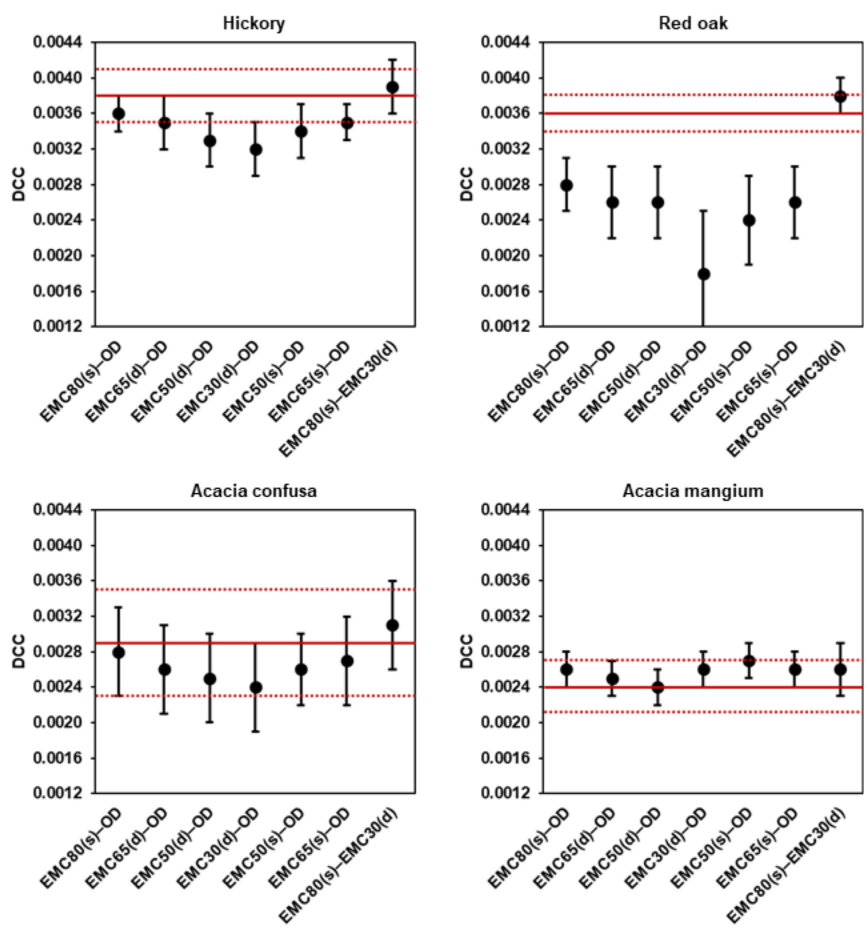

Figure 11—Comparison of DCCs for uninstalled floorboards calculated between two RH conditions (points) (s, sorption; d, desorption; OD, ovendry) with DCCs calculated by linear regression over all RH conditions (solid red lines). The central point represents the mean value, and ranges (error bars and dashed lines) are based on 95% confidence intervals.

Table 9—Influence of floorboard profile on dimensional change coefficient[a]

Species	Number of matched specimens	Regression method[b]		EMC50(s) to ovendry method[c]	
		Mean difference	*p*-value	Mean difference	*p*-value
Hickory	6	–0.0001	0.40	0.0003	0.12
Red oak	7	–0.00002	0.80	–0.00003	0.80
Acacia confusa	10	0.00005	0.79	0.00021	0.22
Acacia mangium	10	–0.00026	0.012	–0.0002	0.006

[a] Statistical results are from paired *t*-tests for matched specimens cut from commercial prefinished flooring with original tongue-and-groove profile versus cut to rectangular profile.
[b] Regression method: see description in Materials and Methods.
[c] EMC50(s) refers to equilibrium moisture content at 50% RH attained by sorption from a lower initial moisture content; see description in Materials and Methods.

Table 10—Dimensional change coefficients for installed floorboards

Species	Mean DCC	95% confidence interval	Estimated measurement error[a]
Hickory	0.0036	±0.0001	±0.0004
Red oak	0.0031	±0.0002	±0.0003
Acacia confusa	0.0032	±0.0002	±0.0004
Acacia mangium	0.0023	±0.0001	±0.0003

[a] Estimated measurement error is based on MC uncertainty values listed in Table 6 and ±0.05 mm uncertainty in width.

between the two board geometries. Only for Acacia mangium are any statistically significant differences observed, with the DCC of tongue-and-groove boards averaging 0.0002 to ~0.0003 lower than for rectangular cuboid boards, and with pairs of matched boards differing by as little as 0.00002 or as much as 0.00069 (data not shown). Acacia confusa and red oak show even smaller mean differences between geometries than does A. mangium. The comparatively large mean difference between geometries in hickory when calculated from EMC at 50% achieved via sorption is not statistically significant despite its magnitude.

We note in Table 9 that although we recover statistically significant differences only in Acacia mangium, even in that wood the differences, 0.0002 to ~0.0003 units, are of no practical importance. That difference is not meaningful given the other variability associated with applying DCCs in a practical context. In addition to variability in the DCC itself, there is uncertainty in width measurements and in moisture content estimation. How these uncertainties work together to influence the ability to calculate conditions at the time of installation or manufacture are treated in Section 3.7.

3.4.5 DCCs for Installed Floorboards

Dimensional change coefficients are reported for installed floorboards in Table 10, using the EMC80(s)–EMC30(d) calculation method described previously. In addition to the mean and 95% confidence interval, the table includes an estimated error in the DCC based on propagation of measurement errors in floorboard width and EMC using Equation (6).

The estimated measurement error for the EMC80(s)–EMC30(d) calculation method is larger than the 95% confidence interval for each species group. The 95% confidence intervals are fairly tight because they reflect the statistical influence of the large number of floorboards in each assembly (between 30 and 36 floorboards).

3.5 Comparison of DCCs for Uninstalled and Installed Floorboards

Dimensional change coefficients for uninstalled floorboards are compared with those for installed floorboards in Table 11. The difference in DCCs determined from the two samples are not significant ($p > 0.05$) for all species groups except red oak. In the case of red oak, the mean DCC for uninstalled floorboards is significantly higher than the mean DCC for installed floorboards. Table 11 also includes the coefficient of variation (COV) for uninstalled and installed floorboards. The COV values indicate that the sample of Acacia confusa floorboards has appreciably more specimen-to-specimen variation than the other species. The COVs for Acacia mangium are identical to the value of 15% given by the *Wood Handbook* (FPL 2010, chap. 4), whereas the COVs for the installed hickory floorboards are lower. The COV for uninstalled red oak boards (8%) is considerably less than the COV for installed red oak boards (14%). Given this difference in COVs for uninstalled and installed red oak boards and the lack of significant difference between DCCs of uninstalled and installed floorboards of the other species

Table 11—Results of unpaired two-sample *t*-test for uninstalled versus installed floorboards

	Mean DCC			COV DCC (%)[a]		DCC interval	
Species	Uninstalled floorboards[b]	Installed floorboards[c]	*p*-value	Uninstalled floorboards	Installed floorboards	Uninstalled floorboards[d]	Installed floorboards[e]
Hickory	0.0038	0.0036	0.13	11	11	0.0035–0.0041	0.0032–0.0040
Red oak	0.0036	0.0031	0.0005	8	14	0.0034–0.0038	0.0028–0.0034
Acacia confusa	0.0029	0.0032	0.41	27	22	0.0023–0.0035	0.0028–0.0036
Acacia mangium	0.0024	0.0023	0.29	15	15	0.0021–0.0027	0.0020–0.0026

[a] COV, coefficient of variation.
[b] Regression calculation method.
[c] EMC80(s)–EMC30(d) calculation method.
[d] 95% confidence interval.
[e] interval based on measurement error.

groups, the difference in red oak DCCs for uninstalled and installed boards may be an artifact of the way the boards were selected for these groups rather than any installation constraint.

The statistically significant difference for red oak also needs to be qualified in light of the effect of measurement error on the DCC values of installed boards, which is not taken into account in the unpaired *t*-test. Measurement error for uninstalled boards is minimal because each specimen had direct gravimetric EMC measured at each condition and DCCs were derived from the regression method over six different EMC conditions. In contrast, the calculated DCCs for the installed floorboards are sensitive to the values of EMC80(s) and EMC30(d), which were not directly measured gravimetrically (see Table 6). In the case of EMC80(s), the value for installed floorboards was based on the gravimetric EMC of uninstalled floorboards under the same conditions. In the case of EMC30(d), the value was based on calibrated moisture meter readings on the installed floorboards. The effect of the uncertainties in EMC conditions and caliper width measurements on the calculated DCCs are shown in Table 10. The corresponding DCC intervals for uninstalled and installed floorboards are listed in Table 11 and visually compared in Figure 12. Considering the effects of measurement error, the mean DCC for the installed red oak floorboards is likely between 0.0028 and 0.0034, whereas the mean DCC for uninstalled red oak floorboards based on the 95% confidence interval is between 0.0034 and 0.0038. The ranges in DCC values thus meet at 0.0034.

3.6 Comparison of Experimentally Determined DCCs with Literature Values

In addition to the tabulated direct comparison of tangential DCCs for uninstalled and installed floorboards in Table 11, in Figure 12 we present the key overall summary graphic of this research—the comparison of experimentally determined DCCs with literature or calculated DCC values and a calculated DCC value for a grain angle of 30°. (Dimensional change coefficients for a grain angle of 30° were calculated using the following general equation based on MacLean (1945): $C_{width}(\theta) = C_T \cos^2(\theta) + C_R \sin^2(\theta)$, where $C_{width}(\theta)$ is the DCC for the width of the board with grain angle θ, C_T is the tangential DCC, and C_R is the radial DCC.) Although we selected the most tangential boards available, even those most-tangential boards often had more than half their width more than 20° off from tangential (Table 12). To account for this grain angle deviation from pure tangential, we present a 30° DCC for illustration. It can be seen in Figure 12 that the clearest pattern is that our measured DCCs are low compared with literature or calculated values (with the exception of Acacia confusa), but those lower values do not uniformly line up with the 30° calculated DCC.

3.7 Practical Methods for Determining DCCs

The *Wood Handbook* includes DCC values for many woods, both domestic and exotic. The list, however, is not exhaustive. When a DCC value is needed for solid wood flooring and the wood is not included in the *Wood Handbook* or other publications, there are several options to determine an appropriate DCC.

If the FSP and the shrinkage value from the green condition to the ovendry condition are available in published literature, then the DCC can be calculated using Equation (3). For this application, the FSP is defined as the moisture content below which the physical properties of wood change as a function of moisture content.

If the FSP or shrinkage value is not available in published data, then the DCC can be determined using measurements on a sample of at least 20 test blocks, each from different boards. Test blocks must have a grain angle as close to purely tangential or purely radial as possible. In this case, the blocks could be conditioned to an equilibrium moisture content within the 6% to 14% range; at equilibrium, the mass and width would be measured; then the test blocks would be ovendried, and mass and width measured again. The DCC of each test block can be calculated using Equation (4), followed by taking the sample mean value. By using the ovendry condition as one reference point for

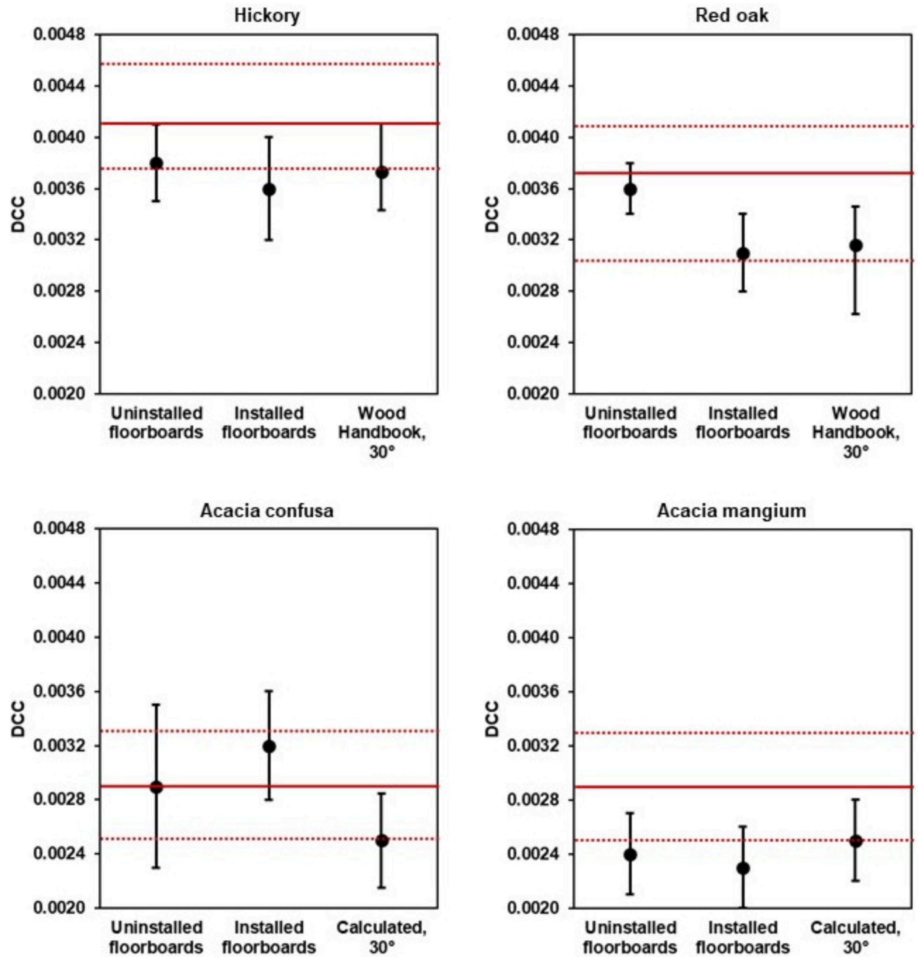

Figure 12—Comparison of measured DCCs for uninstalled floorboards and installed floorboards with values from the Wood Handbook for hickory and red oak, and values calculated from total shrinkage data from the literature for the two Acacia. Central point represents mean value, and ranges for measured values are based on 95% confidence intervals (uninstalled floorboards) and estimated measurement error (installed floorboards). Red lines indicate mean single value tangential DCC (solid red), and dashed lines are based on Tables 3 and 4 for hickory and red oak, respectively, and on analysis in Table 5 for the Acacia.

Table 12—Proportion of board width within 20° of tangential for two board profiles and number of boards in sample with more than 50% of width within 20° of tangential

	Tongue and groove		Rectangular cuboid	
Species	Mean proportion of board width within 20° of tangential, *n* = 10 (S.D.)	No. of specimens with more than 50% of width within 20° of tangential	Mean proportion of board width within 20° of tangential, *n* = 10 (S.D.)	No. of specimens with more than 50% of width within 20° of tangential
Hickory	0.43 (0.1)	3	0.44 (0.3)	2
Red oak	0.33 (0.2)	2	0.29 (0.4)	2
Acacia confusa	0.22 (0.2)	1	0.16 (0.2)	1
Acacia mangium	0.21 (0.1)	0	0.25 (0.2)	1

Table 13—Calculated initial moisture content (at time of remanufacturing) compared with actual[a]

Species	DCC	Measured average final MC (%)	Measured average width (mm) Initial	Final	Initial MC (%) Calculated	Actual
Hickory	0.0041	6.6	77.5	75.5	12.9	13.9
Red oak	0.0037	6.0	76.7	75.1	11.7	12.9
Acacia confusa	0.0029	7.5	91.3	89.4	14.4	14.0
Acacia mangium	0.0029	6.4	89.6	88.3	11.3	12.6

[a] Calculations use average measured final moisture content, average measured dimensions, *Wood Handbook* DCC values for hickory and red oak, and DCC values calculated from the literature for the two Acacia

Table 14—Calculated initial moisture content (at time of remanufacturing) compared with actual[a]

Species	DCC	Measured final MC (%)	Measured width (mm) Initial	Final	Initial MC (%) Calculated	Range of calculated	Actual
Hickory	0.0041	6.6 ± 1.0	77.5 ± 0.2	75.5 ± 0.2	12.9 ± 1.5	11.4–14.4	13.9
Red oak	0.0037	6.0 ± 1.0	76.7 ± 0.2	75.1 ± 0.2	11.7 ± 1.5	10.2–13.2	12.9
Acacia confusa	0.0029	7.5 ± 1.0	91.3 ± 0.2	89.4 ± 0.2	14.4 ± 1.6	12.8–16.0	14.0
Acacia mangium	0.0029	6.4 ± 1.0	89.6 ± 0.2	88.3 ± 0.2	11.3 ± 1.6	9.7–12.9	12.6

[a] Calculations use average measured final moisture content, average measured dimensions, *Wood Handbook* DCC values for hickory and red oak, and DCC values calculated from the literature for the two Acacia. Measurement uncertainties are propagated to yield uncertainty in calculated initial moisture content (Eq. (8)). Uncertainty in the DCC is assumed to be 10% of the value.

width, this method is similar to the procedure that the *Wood Handbook* values are based on. The difference is that this method uses an EMC condition between 6% and 14% as the other reference point for width, rather than the width in the green condition and the FSP value.

The EMC to ovendry method is not recommended for material with grain angle that deviates considerably from purely tangential or radial, because of the possibility of asymmetric shrinkage (cupping or crowning; see Section 3.4.3). In this case, test blocks would be conditioned to EMC at two or more different conditions (between 6% and 14%), followed by ovendrying solely for the purpose of weighing to determine the EMC values. The DCC can be calculated from measured widths and EMC values using Equation (4).

Based on our work in the four woods here, to determine a DCC for a new wood with no reliable green to ovendry shrinkage or FSP values, the highest level of accuracy can be achieved with measurements at three or more EMC conditions for a number of test blocks, and then applying the regression calculation method described in Section 2.6. Although this is the most reliable method, it is also the most labor intensive and requires either multiple controlled conditioning spaces or a chamber that can be set to different RH conditions sequentially. An alternative to mechanical humidity control is the use of saturated salt solutions (ASTM 2020), such as $MgCl_2$ (33% RH) or NaCl (75% RH).

3.8 Example Calculations of Moisture Content at the Time of Manufacture

Ultimately, DCCs are valuable to the flooring industry in order to understand how a floor will behave with changes in moisture content throughout the service life of the floor. The proper application of DCCs in a practical context can allow an installer to estimate average spacing needed at the time of installation if the wood is below the target moisture content, or permit an inspector to calculate the moisture content at the time of manufacture or installation, if necessary parameters are known or measurable. Applying the DCC in this way is useful in the real world but historically has only been done by using a single DCC value, a single, average measurement of moisture content, and a single value for board width (or sum of widths) without allowing for uncertainty in the measurements or the DCCs themselves. We present the analysis of our four flooring assemblies using single values in Table 13. Given our methods for producing the floorboards for the assemblies, we were the "manufacturers," so the actual MC at the time of manufacture is well known. With the exception of Acacia confusa, our calculated initial MC values are ~1% MC lower than actual; that is, our calculations underestimate the MC at time of manufacture.

When considering the single-value result, hickory, red oak, and Acacia mangium are predicted 1.0% to 1.3% MC lower than actual, whereas Acacia confusa is essentially correct (0.4% difference). In Table 14 we extend the analysis to include uncertainties or variability in each of the parameters using Equation (8) (Section 2.9). The uncertainty in measured final MC and width is intended to represent what is practically achievable in an actual inspection rather than a laboratory setting (±1% MC; ±0.2 mm, or ±1/128 in.). The uncertainty in initial width corresponds to the NWFA/NOFMA manufacturing tolerance for factory-finished planks (NWFA 2018). This analysis results in an uncertainty value for the calculated initial moisture content, which is then presented as a range in which the initial moisture content is most likely to fall. In all four cases, the calculated range encompasses the actual initial moisture content. By incorporating uncertainty in our measurements and DCCs, we recover a range of values that in each case includes the true value. Using estimates of variability for each parameter provides a scientifically justifiable method to calculate the likely range of MCs at the time of manufacture.

Calculating and reporting a range of MCs at the time of manufacture is perhaps less convenient than using a single value, but it more realistically represents the accuracy with which one can measure these properties in the field. It is also noteworthy that when calculating prior MCs in a scenario where gapping is the result of a high initial MC (that is, at the time of installation or manufacture), using the purely tangential DCC gives every benefit of the doubt to the installer or manufacturer, because a larger DCC predicts a smaller change in MC for the same change in board dimension, meaning that an installer or manufacturer would be "closer" to the targeted MC for a given dimensional change. This is likely not realistic, because boards that are truly tangential across their entire width are not the norm. Especially with wider plank-type floorboards (for example, 5 or 6 in. wide), there is almost no chance than any board will even be a majority true tangential. With a grain angle of –20° to +20°, the effective DCC is within ~90% of the pure tangential value, and any grain angle greater than that pushes the effective DCC progressively closer to the radial DCC for that species. This is a key detail for inspectors, installers, and homeowners to understand when applying DCCs to installed floors. It is not practical to determine the exact grain angle of installed boards, so assuming a pure tangential value for DCC is the most generous approach.

Attached in the digital version of this paper (and see Appendix) is an Excel (Microsoft, Redmond, Washington) spreadsheet that enables the user to run calculations similar to those described above. The user may enter the DCC value, the measured final moisture content and width, and the specified manufactured width, and the spreadsheet calculates the moisture content at the time of manufacture. In addition, the user may enter uncertainties for each value, and the spreadsheet calculates the probable range of moisture content values at the time of manufacture. These calculations take place automatically in the background.

Going forward, a useful solution may be to develop a smartphone app or other electronic tool more portable and adaptable than the spreadsheet we provide here.

4 Conclusions

We provide time-lapse videos for each wood type, showing a close-up view of just a few boards, and a lower magnification showing wood shrinkage and swelling across several boards.

This paper examines prior FPL literature on dimensional change coefficients (DCCs). We derive an equation for calculating DCCs based on fiber saturation point and shrinkage from the green to ovendry condition (in either the tangential or radial direction), and we show that this equation gives identical DCCs to those listed in the *Wood Handbook* for the hickory group, the commercial red oak group, and 12 other wood species.

We recommend that DCCs be reported to two significant figures because of the variability underlying the DCCs in the *Wood Handbook*, as well as the variability in DCCs experimentally observed here.

We present calculated DCC values for both Acacia based on green to ovendry shrinkage reported in the literature and a reported or assumed FSP.

Our data indicate that surface finish does not appreciably affect EMC or calculations of wood specific gravity, at least in specimens of the sizes studied here.

We demonstrate no practical difference in DCC for tongue-and-groove floorboards compared to rectangular cuboids, so using DCCs measured from rectangular cuboids appears to be acceptable.

We compare our experimentally determined DCCs for uninstalled and installed floorboards and determined that there is no practical installation constraint on shrinkage of installed floorboards.

We demonstrate that our experimentally determined DCCs for hickory and red oak are within a reasonable range of *Wood Handbook* values, and our experimentally determined values for the Acacia are within a reasonable range of calculated DCC values.

We present practical methods for determining DCCs for species that are not included in published data.

We demonstrate that calculating moisture content at the time of manufacture by incorporating variability in width measurement, moisture content, and DCC results in a range of initial MCs that spans the actual MC, whereas using single, average values does not accurately predict the initial MC in three of four cases.

Acknowledgments

This project was jointly supported by the Forest Products Laboratory and the Flooring Inspectors Education Guild. The authors thank Mr. Richard Soares and Mr. Bob Munson for diligent measurements of specimen widths, masses, and moisture meter readings—we wish Bob the best in his retirement. The authors thank Mr. Tom Miessler from LW Mountain for his generous donation of the Acacia materials for this study and Mr. Tim Nathan of General Finishes and Mr. Mike Wagner of Wagner Flooring for installing the floorboards to the subfloor assemblies. We thank the Flooring Inspectors Education Guild for their patience and support throughout this project. Finally, we thank three reviewers for helpful comments that improved this paper.

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Appendix—Supplementary Material

Time-Lapse Videos

The following time-lapse videos for each wood type, showing a close-up view of just a few boards and a wider view across several boards, are available to download and view on your device.

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/A_high.avi (163 MB) Acacia mangium, high magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/A_medium.avi (146 MB) Acacia mangium, medium magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/B_high.avi (156 MB) Red oak, high magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/B_medium.avi (160 MB) Red oak, medium magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/C_high.avi (125 MB) Hickory, high magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/C_medium.avi (104 MB) Hickory, medium magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/D_high.avi (193 MB) Acacia confusa, high magnification

https://www.fpl.fs.usda.gov/video/fpl_rp711_supp/D_medium.avi (173 MB) Acacia confusa, medium magnification

Wood Dimensional Change & Moisture Content Calculator

Any updates to the calculator spreadsheet will be available to download at https://www.fpl.fs.usda.gov/documnts/fplrp/fpl_rp711/dimensional-change-calculator.xlsx