Final Report
Project NT013

Sensing technology and digital tools to support decision-making in hardwood timber drying

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NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION LAUNCESTON

Sensing technology and digital tools to support decision-making in hardwood timber drying

Prepared for

National Institute for Forest Products Innovation

Launceston

by

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Introduction

This is the final technical report for the National Institute for Forest Products Innovation's (NIPFI) project: *NT013 / NIF077 Sensing technology and digital tools to support decision-making in hardwood timber drying.*

The quality of the hardwood drying strongly influences the profitability of milling. Timber boards dried without induced drying degrade can be sold at a premium as differentiated appearance products for architectural applications. However, material with the features of drying degrade such as checks and splits is not accepted in the appearance product market and must compete against commodity softwoods in structural and industrial markets, where the price received may not cover log procurement and processing costs. The outcome of avoidable drying degrade for the producer is the combined loss of the product's market value and the unavoidable burden of high production cost.

While critical to production, few tools currently exist to assist mill and yard managers in their day-to-day drying management decisions. However, the reduced cost of sensors, data management and processing techniques, and the increased value of quality hardwood creates an opportunity for a sensing-based applications that allow yard managers to monitor the timber's drying behaviour confidently, compare relative drying conditions at different yard locations, model long-term drying and yard performance given known and projected climatic conditions, and control day-to-day yard management for optimal production.

This project aimed to develop and validate a timber drying technology suite with an accompanying decision-making support tool, the Hardwood Improved Air Drying (HI AirDry) application for higher value product recovery across the wider hardwood Industry. It focuses on improving the connection between hardwood air drying and the recovery of product value from processed logs.

This is the second of two technical reports for this project. The first report TR-S1 provides a summary of the project and its findings while this technical report TR-1 details the methodology and results of the application's development and validation.

Acknowledgements

The project team would like to thank its major industry collaborators: Britton Timbers; McKay Timbers; Neville Smith Forest Products (NSFP); and Porta Mouldings, whose staff contributed both time and their expertise to make this project possible.

Project overview

This project was designed to extend, improve, and validate a limited prototype sensing technology and simulation decision support tool developed by Centre for Sustainable Architecture with Wood (CSAW) staff in a Sense-T funded project in 2017. As developed, the project aims and is structured to employ state-of-the-art information sensing, modeling technology monitoring and data platforms to provide drying yard managers with an industry-friendly decision-making support tool that can improve recovery and maintain hardwood board quality and value during air-dry sawn boards to fibre saturation point (FSP). This is intended to support a significant increase in hardwood producer profitability by reducing loss through avoidable degrade, increasing recovery through adoption of less conservative milling tolerances, and improving scheduling of product through mills.

Project deliverables include:

- An active decision support tool 'app', the Hardwood Improved Air Drying (HI AirDry) application, and a pilot-scale suite of microclimate sensing equipment.
- Operational guidelines for installation and implementation of the above technology in a wider production phase with Australian hardwood producers.
- Presentation of any improvements in the management of hardwood timber's moisture content (MC) made during the application's implementation, validation, and refinement.

Methodology

The methodology's scope covers air-drying of Tasmanian hardwood in conventional timber drying yards. See Figure 1. Primary project collaborators and location of their drying yards used in the project include:

- Britton Timbers, with a drying yard at Smithton in northern Tasmania.

- McKay Timbers, with drying yards at Brighton and Glenorchy in southern Tasmania.
- Neville Smith Forest Products (NSFP), with a drying yard at Mowbray in northern Tasmania.
- Porta Mouldings, with a drying yard at Bridgewater in southern Tasmania.

Figure 1: Conventional hardwood drying yard: line stacked

The methodology's sub-programs included:

1. Production and material data collection.
2. Computer model development.
3. System Application development.
4. Industry adoption.

The first three sub-programs deal with the HI AirDry app's development and can be organised into the components shown in Figure 2.

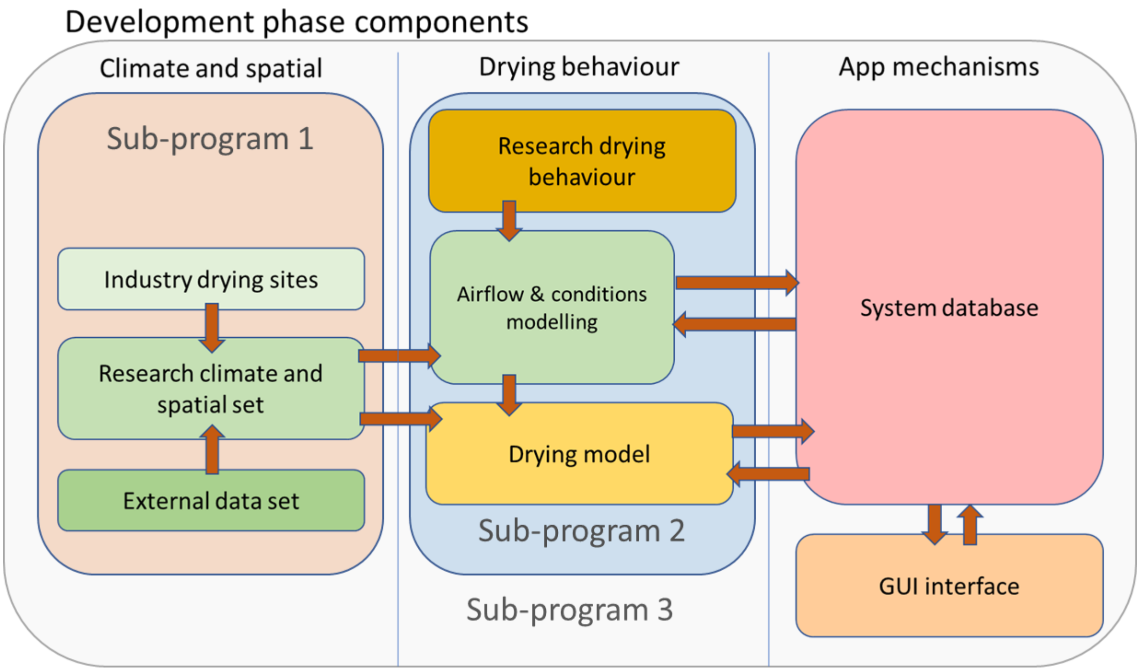


Figure 2: Decision support application components

In practice, two collaborative teams worked on the project. The first team, led by Associate Professor Peter Doe, included School of Engineering and CSAW staff, and worked on sub-program 1 and 2, focusing on production and material data collection and Computer Fluid Dynamics (CFD) modelling to provide KILNSCHED's necessary climatic and other inputs and validate results in the drying yards.

The second team, led by Tony Gray, included School of information and Computer Technology (ICT) staff and students, and worked on the application's computer and information systems and interfaces.

Production and material data collection

Additional material and site information was required to increase the accuracy and flexibility of computer model used in the air-drying improvement app. This included extended measurement of the materials' physical properties, timber's drying in racks and stacks, and the atmospheric condition in yards and around stacks. Activity in this sub-program included:

- Determine the physical arrangement of the site and adjacent areas.
- Extend site data sets to additional locations, exposure conditions and species.
- Capturing climatic information necessary to validate the drying model.

Computer model development

Development of the timber drying and yard condition model that aimed to increase the air-drying improvement app's accuracy and flexibility. The methodology for modelling timber drying was refined and advanced Computational Fluid Dynamics (CFD) modelling was used to simulate airflow around the timber and surrounding environment. These then were then combined to produce a drying estimate for each rack. Activity in this sub-program includes:

- Drying model enhancement.
- CFD modelling and estimation of airflow at sites.
- Validating the model components against measured performance at industry sites.
- Integrating the KILNSCHED model.

System Application development

A 'first-generation' industry-friendly Hardwood Improved Air Drying (HI AirDry) application for monitoring and decision-making support for hardwood air-drying was developed from the available components: the site sensing set; the data storage pool; the computer model and their output and a system that provides users with desktop and tablet-based interfaces. Activity in this sub-program included implementing a system application that includes:

- Establishing the data structure
- Developing and testing process for operational data collection.
- Configuring systems to working application.

Industry adoption

The developed air-drying improvement application and potential product improvements were demonstrated to industry members at a management and operational level. Activity in this sub-program includes:

- Involving industry members in the program.
- Field trial, refinement and rollout of the user interfaces and apps.

Production and material data collection

This stage provided the climate and spatial information required to inform and increase the accuracy and flexibility of the air-drying improvement app's computer drying model. It included:

- Determining the physical arrangement of the site and adjacent areas.
- Extending site data sets to additional locations, exposure conditions and species.
- Capturing climatic and material information necessary to validate the drying model.

Establishing the data storage structure for this information is part of *Sub-program 3.*

Results

Site's physical arrangement

The site physical arrangement is required to:

- Provide the accurate three-dimensional models of the sites and surrounding areas needed for CFD modelling. This is part of computer model development, discussed below.
- Establish rack location systems for use operationally in the HI-AirDry application.

As the locational accuracy necessary for CFD modelling is significantly higher than that needed for a rack location system, its requirements governed the selected site survey methods. Drone surveys proved to be the most efficient means of collecting the spatial information of the drying areas and surrounding buildings, while public topographical information was used to determine the spatial arrangement of surrounding areas.

Drone survey of site

UTAS School of Geography, Planning, and Spatial Sciences (GPSS) and CSAW staff collaborated to conducts drone surveys of industry mills from mid-2021 to early 2022. See Figure 3 and Figure 4. Composite images for each site were assembled and are included in Figure 5.

Figure 3: Confirming the position of GPS plates

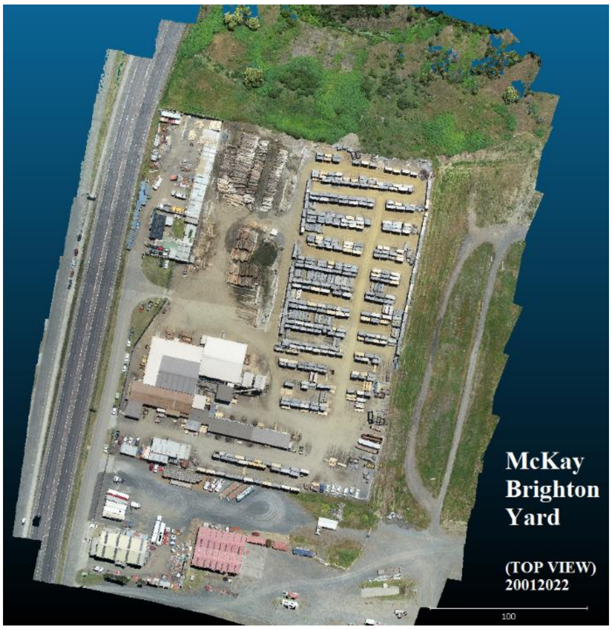
Figure 4: Survey drone

The drone survey used a DJI Phantom 4 Pro drone at a flying height of 120m (Above Ground Level, AGL). Around 250-300 photos were taken of each large site and approximately 100 photos of the smaller sites, each with a forward and side overlap of 80%. Seven to 10 Propeller AeroPoints ground control points (GCPs) were used as ground control at each site. Accurately GPS located, these provided known reference points in each images. The imagery was processed in Agisoft MetaShape using photogrammetric structure from motion processing to produce image orthomosaics at a resolution of approximately 3-3.1cm, 3D meshes with 4-5 million faces and point clouds with approximately 260 points per square metre.

The GCPs were identified in each image prior to dense 3D model generation. The absolute accuracy of the resulting datasets is approximately 3-5cm. See Figure 6.

Britton Timbers' Smithton West drying yard

Britton Timbers' Smithton East drying yard



McKay Timbers' Brighton drying yard

McKay Timbers' Glenorchy drying yard

NSFP's Mowbray drying yard

Porta Mouldings Bridgewater drying yard

Figure 5: Drone-captured images of collaborator drying yards

Figure 6: Detail of timber stacks captured in the drone survey

Site model generation

In preparation for the CFD modelling, the Point Clouds® datasets for each site were converted into a three-dimensional model, with specific coordinates, dimensions, and heights of all the major buildings, paths, and timber racks extracted manually using CloudCompare® V2.12. The resulting model approximated each stack as a vertical rectangular column with its base at the drone-located position and height to an accuracy of a few millimetres. Fully or partially empty rows were reintroduced to the model. See Figure 7

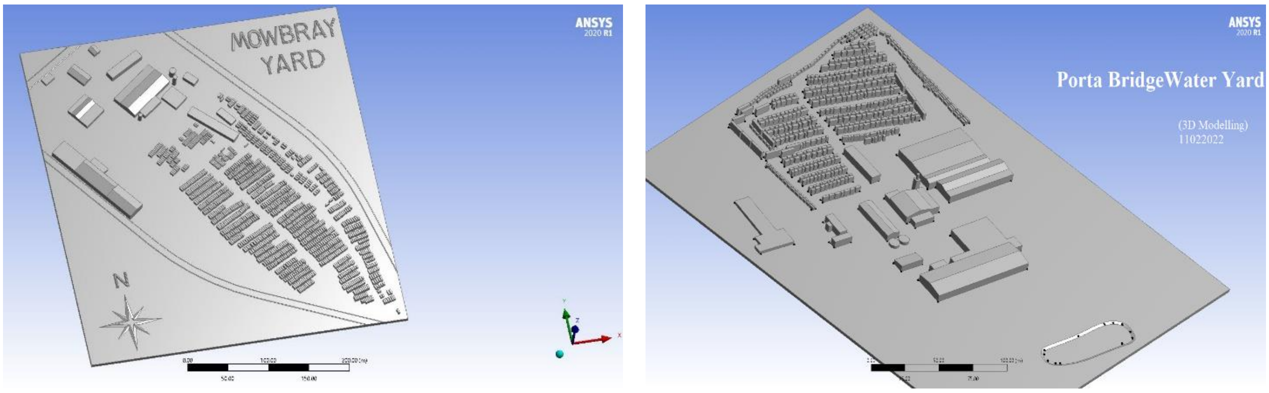
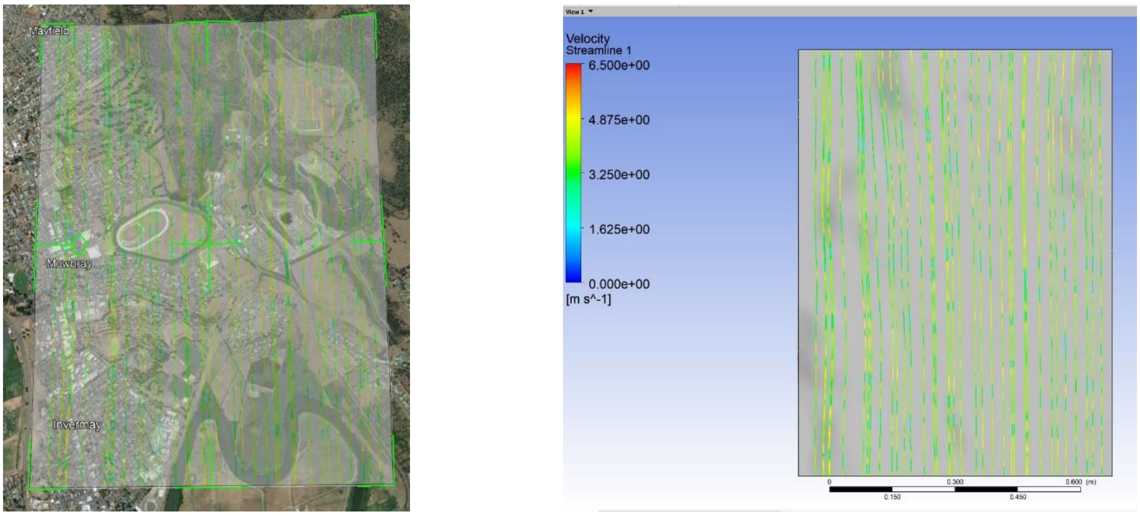


Figure 7: Three-dimensional site model generated from the drone data for industry sites.

Surrounding area model generation

Public topographical information provided the spatial arrangement of areas surrounding the drying yard and was used to generate an area surface model. See Figure 8.



Topographical model overlayed on site | **Topographical model with air flow**

Figure 8: Topographical model for NSFP's Mowbray drying yard

Extending site data sets

Sensors and other devices were required to collect:

- The local climatic information used operationally in the HI-AirDry app.
- Airflow and timber drying information required for computer model validation

The capacity to collect additional site data was enhanced with an expanded sensor monitoring suite, and data collection on industry sites was extended. In addition to weather station, additional sensors and traditional sample boards were deployed to collect climate and material information across sites.

Operational climate information

Working with the UTAS data collection group, Sense-T, a reliable sensor monitoring suite was assessed and acquired to collect adequate climatic information about the drying sites. This included weather stations, detailed in Table 2 and shown in Figure 11. These were used in validation trials at different locations and in mid-2022, weather stations were installed at each collaborating mill. See Figure 9 and Figure 10.

Figure 9: Weather station at McKay Timber, Glenorchy

Figure 10: Weather station at Porta Mouldings, Bridgewater

BOM data from weather stations was sourced and compared to site collected data for use in the application's compacted 'climate library'. Table 1 shows the relative location of mills and BOM stations.

Table 1: Relative mill and BOM station locations

Mill location	BOM station location	Distance
NSFP Mowbray	Launceston TAS; station number: 091237	2.7 km
Brittons Smithton	Smithton TAS; station number: 091292	3 km
Somerset	Wynyard TAS; station number: 091107	9 km
Brighton	Campania TAS; station number: 094212	14 km
Glenorchy	Hobart TAS; station number: 094029	6 km

Sensing for model validation

In addition to weather station, additional sensors and traditional sample boards were deployed to collect climate and material information across sites. This was to satisfy operational and validation tasks in other sub-programs. Table 2 list the name and key characteristics of the sensors in the suite.

To extend historic data sets, weather stations and other sensor units operated at Brittons at Smithton, NSFP at Mowbray and McKay's at Glenorchy since early 2020 with the data recorded in a Sense-T platform.

Sample boards were used to indicate the actual drying of timber in the rack. These are length of timber with a known initial MC that are removed from the rack and weighed regularly. The change in board weight allow the board's MC to be determined accurately, and this is used as a surrogate for drying of all boards in centre of the rack.

Table 2: Project climate sensor suite

Sensor type	Features	No	Notes
Sense-T weather station	Humidity; Temperature; Vapor pressure; Atmospheric pressure; Wind direction; Wind speed; and Gust speed	6	This is a purpose-built set of sensor units connected by mobile phone telemetry to the Senaps (Sense-T online) platform. See Figure 11
Anemometer	Humidity; Temperature; Wind direction; Wind speed	5	This sensor is one of the units in the weather stations and stores data on a local SD card with a nom. 2 weeks' capacity. See Figure 12.
Sense-T sensors	Humidity; Temperature	5	A small purpose-built sensor that connects to the weather stations locally. See Figure 13.
Minnow sensors	Humidity; Temperature	5	A low-cost and versatile unit for confirming humidity and temperature between racks. See Figure 14

Figure 11: Sense-T weather station

Figure 12: Sense-T Anemometer

Figure 13: Sense-T sensors

Figure 14: Minnow sensors in ply protector

Capturing climatic and material information for validation

Climatic and material information was required to validate the effectiveness of CFD modelling of airflow and the drying model's predictions of timber drying. This occurred in several stages:

- Broad area assessment of airflow at NSFP's Mowbray site.
- Detailed assessment of *E. nitens* drying at NSFP's Mowbray site.

- Sample collection at NSFP's Mowbray and McKay's Brighton site.

Data collection from NSFP's Mowbray site

The NSFP Mowbray drying yard was used as the test site for drying model development and validation.

Figure 15: Sensor location map for NSFP Mowbray

Five weather stations and five anemometers were installed at the NSFP Mowbray yard on 2 June 2021 in the configuration shown in Figure 15. Readings of wind speed, direction, air temperature and humidity were streamed into the Sense-T data platform from the weather stations every 10 minutes. The anemometers also recorded wind speed and air conditions with the data stored on each machine and transferred to the Sense-T platform fortnightly. Concurrent BOM data from the Ti-Tree bend station (2.7 km due west of the NSFP Mowbray site) was obtained and compared to the streamed data to determine if historic BOM data could be used to provide the application's compacted 'climate library'. The site collected data sets were used to assess the accuracy and evaluate the usefulness of CFD modelling.

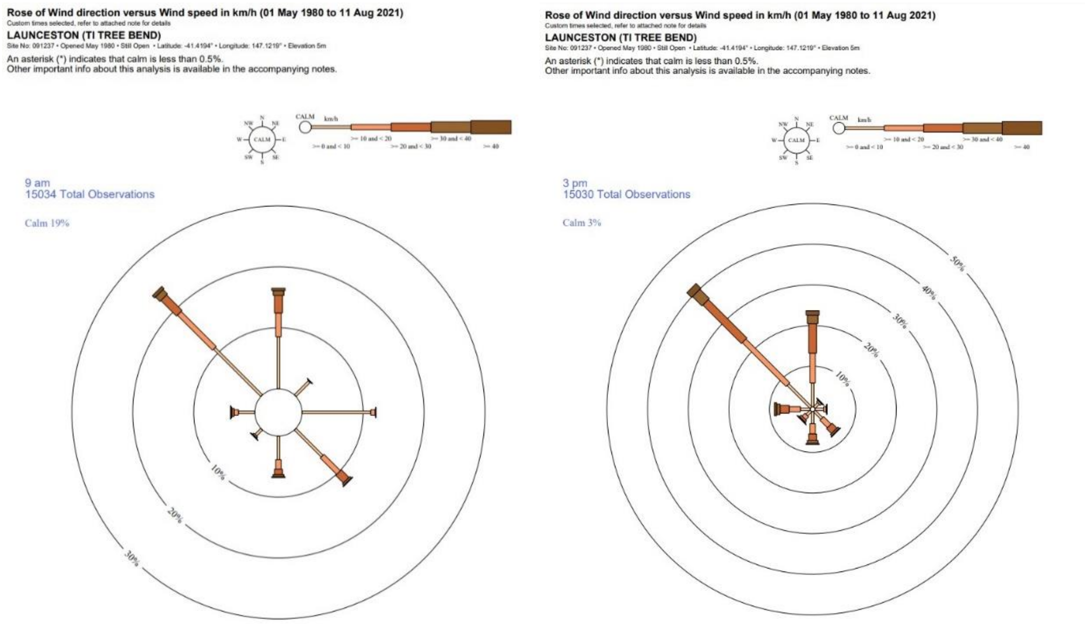


Figure 16: Wind roses from the BOM Ti-Tree station (41 Years' data).

Results indicate that the BOM data can provide sufficient accuracy to augmenting CFD modelling and climate profiles for the NSFP Mowbray yard due to the relatively flat local topography and the predominant Northwest wind direction shown in Figure 16.

E. nitens drying assessment

From 1 March 2021 to 28 September 2021. CSAW monitored the drying of a rack of 26mm backsawn *E. nitens* boards located at the southern end of the NSFP Mowbray yard using weather stations, anemometers and Minnow sensors. Sample boards were established in several racks and weighed at roughly 2-week intervals and average MC calculated.

These results were then used for drying model validation, discussed below.

Figure 17: Monitoring *E. nitens* packs at NSFP Mowbray

Production rack sample collection

In June and July 2022, racks with known production dates and characteristics were identified at McKay Timbers' Brighton and NSFP Mowbray site to represent the diversity of drying conditions at the two sites. Selected racks had varied board thickness and estimated site air-movement.

In associate with site staff, the racks were recovered from the drying yards, split with a forklift, and samples were collected from boards at the centre of each rack. See Figure 18 and Figure 19. The samples were identified with their rack number, wrapped in plastic and the MC was assessed by oven drying to AS 1080.1. These results were then used in the validation discussed below.

Figure 18: Samples collection at McKay Timbers' Brighton

Figure 19: Samples collection at NSFP Mowbray

Computer model development

This stage includes the development of the mechanisms required to reliably generate useful estimates of the drying condition at yard locations and the progressive drying of boards in rack given prevailing climatic conditions. This included:

- Drying model enhancement.
- CFD modelling and estimation of airflow at sites.
- Validating the model components against measured performance at industry sites.
- Integrating the KILNSCHED model.

Results

Drying model enhancement (DME)

School of Engineering engineers originally developed the UTAS's drying model KILNSCHED in the 1980s and 1990s and CSAW and Sense -T engineers upgraded it in 2016. During its initial development, the physical properties of Tasmania Oak timber and other species were measured, and the results incorporated into a computer program that calculates the changes in MC and the stresses within boards as they dry. The computer model was verified by drying boards in wind tunnels and small kilns with accurately controlled temperature and humidity.

Unlike the relative stable and predictable conditions in kilns, conditions in air drying yards are highly variable as wind speed and direction, air temperature and humidity can change from minute to minute and different locations around a yard will experience slower or faster drying. These changing conditions all affect the drying rate of boards in a rack and have to be accommodated in any effective drying model. The 2016 version of KILSCHED included all the functionality of the original but was linked to the Sense-T climate data base. It used climatic information recorded at timber yards as inputs into the drying model.

Drying model enhancement in this project focused on increasing KILNSCHED's capacity to better accommodate the fluctuating conditions in drying yards.

CFD modelling and estimating airspeed

Airflow speed and direction are two KILNSCHED variables affected by the drying yard's regularly changing conditions. Unlike controlled timber drying kilns, air-drying yards do not have controlled airspeed, temperature, and humidity. These variables fluctuate continually throughout the day in the ambient conditions around the site and change in the drying yard in a way moderated by buildings and timber stacks. To generate a useful basis of estimating the airspeed variables used in KILNSCHED, this stage included:

- CFD modelling of the drying site
- CFD modelling of the surrounding area
- Airflow estimation for sites.

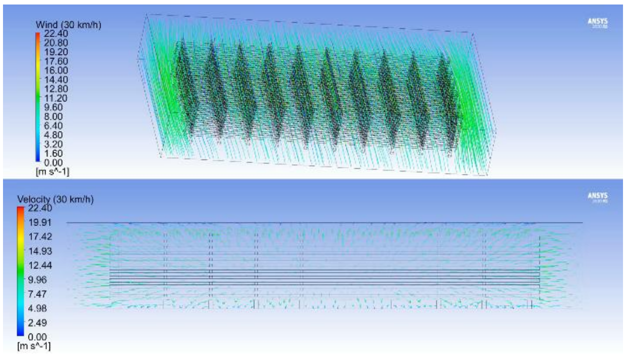
CFD modelling of drying yard

CFD is widely used to model and simulate airflow in and around buildings. In this project, the FLUENT component of the ANSYS CFD software was used to model the steady state airflow direction and magnitude patterns around and between timber stacks at project collaborators' air drying yards. It does not model variation in other variables, such temperature or humidity.

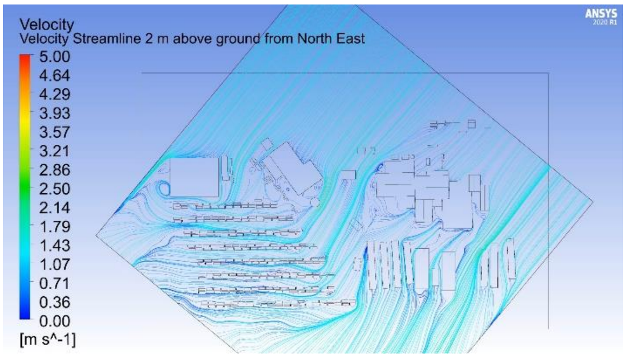
CFP modelling on a site as complex as a large timber drying yard requires considerable time and computer capacity. Each ANSYS/FLUENT run performs numerous iterations, each generating outputs that are used as inputs in later iterations. This continues until the program settles on a consistent final value for air movement in each location. Given the computer time and capacity required, it is not practical to calculate wind speeds at every point in a yard on a continual basis.

Initial modelling investigated airflow through an individual rack. However, this level of detail was found to be too complex and expensive to model for a whole yard and subsequent simulations modelled the stacks as solid blocks.

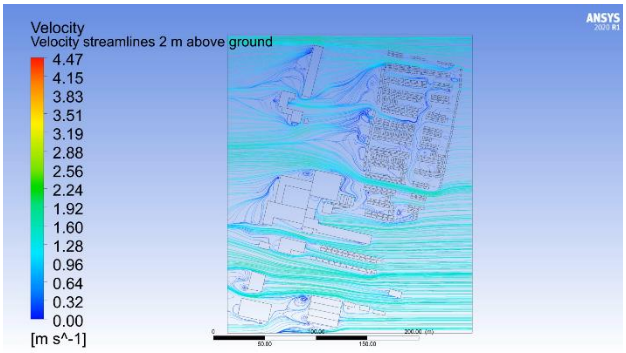
Using the three dimensional model developed from the site survey data, sixteen CFD simulation were generated for each site. These were based on eight wind directions: North, South, East, West, Northeast, Northwest, South-west, and South-east; and two wind magnitudes for each wind direction: 5 km/h and 20 km/h. Each simulation generated airflow information in a tabulated form and graphically as a video. Figure 20 shows images taken from a simulation for each modelled sites. Colours in the video and images shown how some stacks experience higher or lower local airflow depending on the wind direction and yard position.



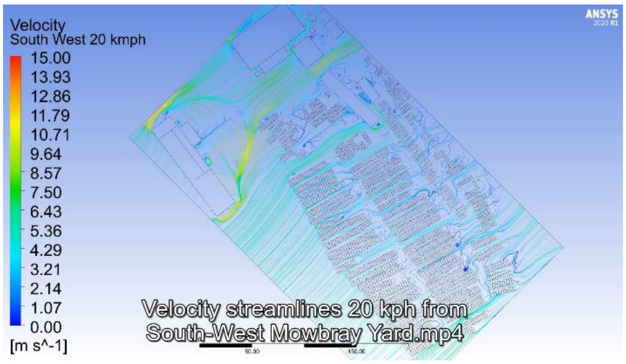
CFD modelling of an individual rack



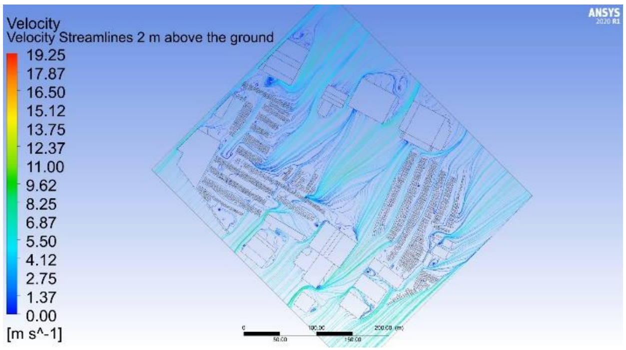
Britton Timbers' Smithton West drying yard



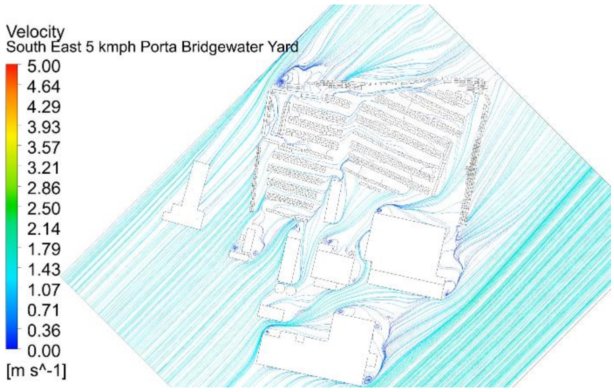
McKay Timbers' Brighton drying yard



NSFP's Mowbray drying yard



McKay Timbers' Glenorchy drying yard

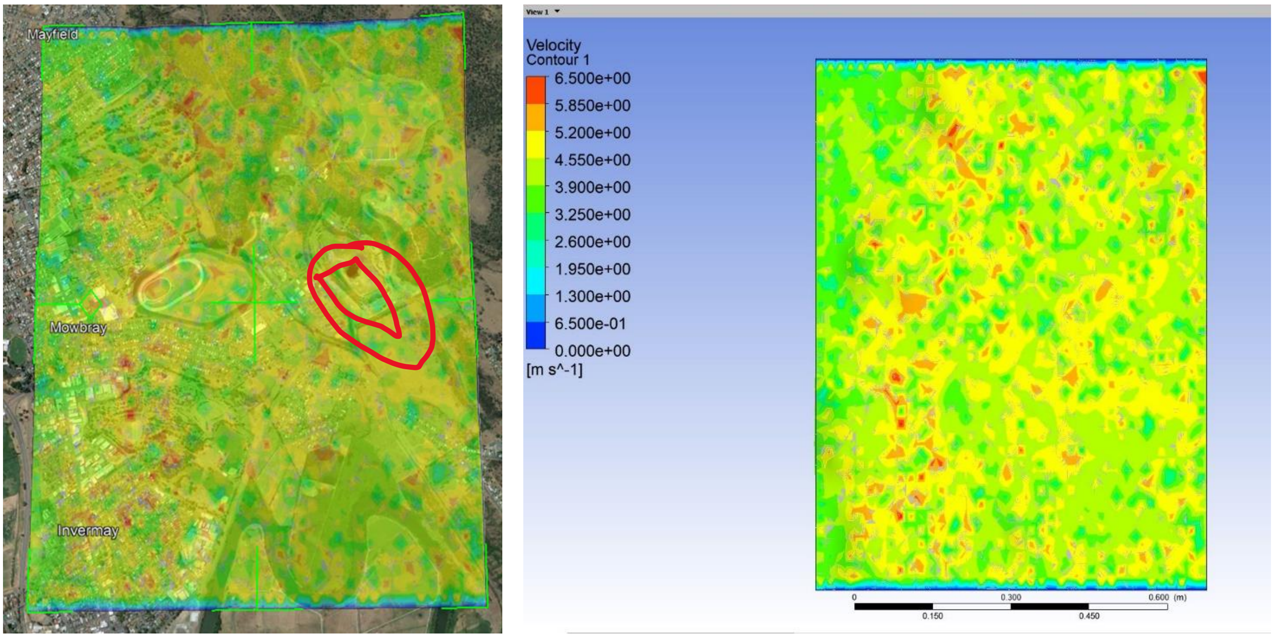


Porta Mouldings Bridgewater drying yard

Figure 20: : CFD modelling of rack and industry air drying yards

CFD modelling of the surrounding area

Topographical characteristics can influence the speed, direction and pattern of air flowing into the drying yard. To investigate these effects, CFD simulations were performed using the area surface model surface models described above, for four wind directions: north, south, east, and west. Again, this generated airflow information in a tabulated form and graphically as a video. Figure 21 shows an image taken from one simulation for NSFP's Mowbray drying yard.



NSFP's Mowbray drying yard NSFP's Mowbray drying yard

Figure 21: CFD modelling of the area surrounding air drying yards

Airflow estimation for site

Airflow speed and direction are important drying variables. While CFD is a powerful and informative modelling tool, any modelling of physical processes can only approximate reality. The challenges that became apparent in incorporating CFD airflow results directly into a model such as KILNSCHED include:

- CFD can generate estimates of airflow between and around timber stacks, but the required input data for the KILNSCHED drying model is airflow across the board. However, modelling yards to this level of detail was impractical.
- Airflow is not constant in magnitude or direction. It fluctuates continually. However, given CFD's complexity, it is not practical to calculate wind speeds at every point in a yard on a continual basis.
- Air flow entering the CFD 'control space' may not be uniform because of the surrounding topography and off-site buildings.
- CFD only models airflow and not other local variables, such as temperature and humidity.

CFD site modelling's principal benefit appears to be as a heuristic indicator of stack locations susceptible to rapid or slow drying rather than, as originally intended, as direct input to the KILNSCHED model.

The sensitivity of KILNSCHED results to varying airspeed was also modelled. The results show that KILNSCHED is relatively insensitive to airspeed though, as expected, it is sensitive to board thickness. The insensitivity to airspeed is due to the short period of constant rate drying in which the evaporation from the surface of a board is highly air-speed dependent. See Figure 22.

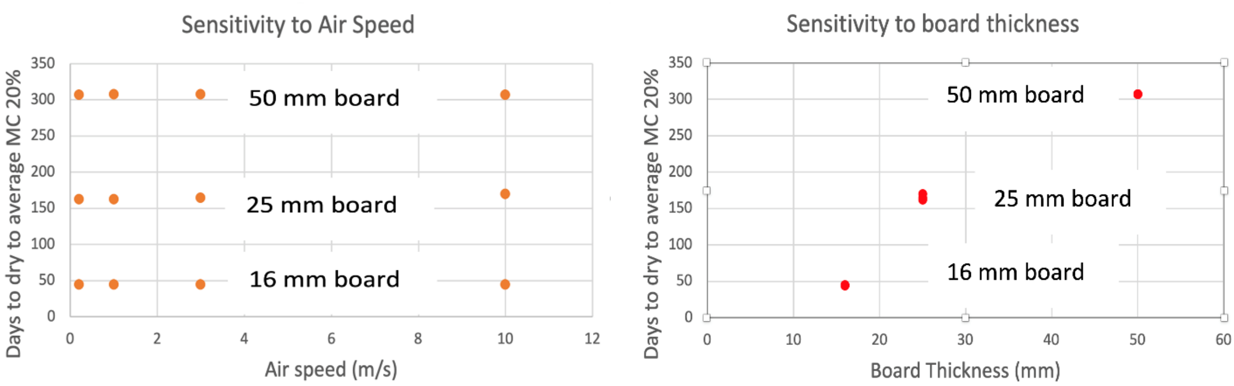


Figure 22: KILNSCHED's sensitivity to airspeed and board thickness

Given these results, two factors were incorporated into the system to allow for abnormal yard drying:

- Racks at ends of rows (where abnormal drying is likely) are uniquely identified during data collection and variable preparation.
- An additional factor PN has been incorporated into KILNSCHED and designated to rack location after review of the simulations and discussions with site drying yard managers. The factors are
    - PN = 1 is assigned when a rack is expected to experience lower than normal internal airspeed.
    - PN = 2 is for the majority of racks expected to experience internal air speeds around 0.5 m/s (1.8 km/hour).
    - PN = 3 for those racks likely to be experiencing higher than normal airspeeds.

Dynamic PN assignment using CFD results was also assessed and may be viable with further development.

As the board's MC will not change minute-by-minute as the wind changes in speed and direction, a wind flow averaging approach was adopted and the system configured to:

- Average wind speeds and the predominant wind direction over a set period from the on-site weather station anemometers readings, or projected BOM data.
- Use the appropriate PN value for that wind speed and direction.

Validation against measured air-dried stacks at industry sites

In addition to data comparison of climate and airflow results from various sources, two validation exercises were conducted: the 2021 *E. nitens* drying assessment and the 2022 production rack assessment

2021 E. nitens drying assessment

As outline above, from 1 March 2021 to 28 September 2021 CSAW monitored the drying of racks of backsawn *E. nitens* boards located at the southern end of the NSFP Mowbray yard. Sample boards were weighed at roughly 2-week intervals and average MC calculated.

The HI AirDry app was run using the results of this monitoring and available BOM climate data from the nearest station (Ti -Tree bend). Figure 6 shows the measured MCs and the computed average MCs with a mass diffusivity of 1.2 x 10 $^{-7}$ m^2/hr. Different values of the PN (PN=1, PN=3) factor made little difference to the computed drying rate. Figure 7 shows the variation of temperature and humidity at the time.

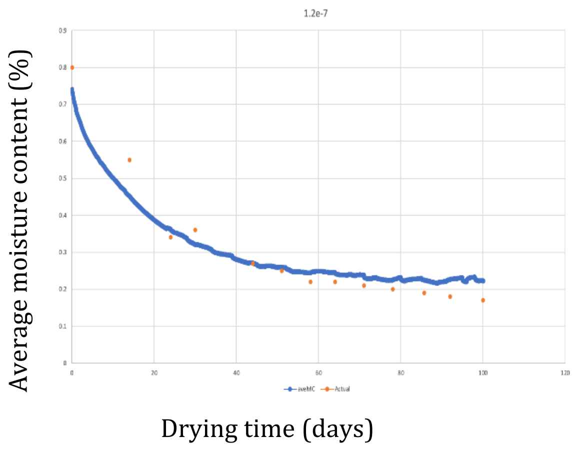


Figure 23: *E. nitens* rack – drying curve

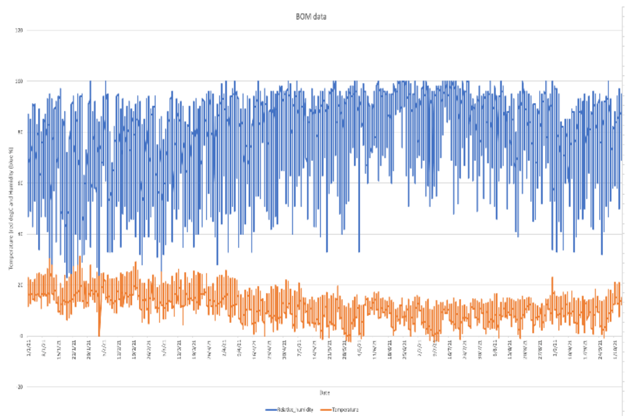


Figure 24: Climate data from BOM

2022 validation run

In July/August 2022, a total of 20 boards were removed from the centre of racks that had been placed and recorded on the HI AirDry app in November/December 2021 at NSFP yards and March/April 2022 at the McKay Brighton yards. 30cm samples were docked from the centres of the boards, wrapped in plastic and their MCs measured at the CSAW laboratory in Newnham. The results are given in Table 3.

Table 3: MC and dry density of sample boards.

Yard	Rack ID	Sample board	Nom. board dimensions	Ave MC (%)	Core MC (%)	Case MC (%)	thickness (mm)	Basic density (kg/m3)
McKay	54949	1	100x16	23.50	23.54	22.77	15.6	631.6
McKay	54949	2	100x16	32.53	35.21	28.21		
McKay	54959	1	100x38	47.81	57.82	33.59	40.3	440.2
McKay	54959	2	100x38	81.79	118.83	53.79		
McKay	54953	1	100x38	55.23	78.02	38.07	40.1	636.7
McKay	54953	2	100x38	47.65	62.47	40.77		
McKay	54867	1	150x25	37.35	47.66	29.88	23.0	660.4
McKay	54867	2	150x25	32.24	39.08	26.62		
McKay	54873	1	150x19	20.88	21.48	20.45	18.9	642.8
McKay	54873	2	150x19	20.81	21.31	19.79		
McKay	54825	1	125x25	24.35	28.40	24.11	25.9	615.3
McKay	54825	2	125x25	25.26	25.76	23.63		
NSFP	02659	1	150x25	17.92	18.17	17.83	25.6	574
NSFP	02659	2	150x25	18.43	17.91	18.46	25.7	547
NSFP	02698	1	125x25	18.16	18.98	17.96	26.2	588
NSFP	02698	2	125x25	18.98	19.30	18.46	26.6	575
NSFP	02699	1	125x25	17.34	17.73	17.70	23.6	749
NSFP	02699	2	125x25	17.31	17.75	17.66	23.4	747
NSFP	44437	1	125x25	16.88	17.87	17.13	25.3	566
NSFP	44437	2	125x25	17.03	17.55	16.93	25.4	571

To inform the likely values of KILNSCHED variable for initial MC and basic density, nine samples were collected from boards green off the saw to racking at McKay Brighton mill on 21 July 2022. Table 4 reports the thickness, MC and basic density of these samples when assessed to AS 1080.1

Table 4: Variation in MC off saw

Sample thickness (mm)	Moisture content (%)	Basic Density (kg/m3)
42.6	91.7	570
39.6	84.8	580
43.5	93.3	581
44.1	111.2	382
27.9	93.4	583
44.1	97.6	536
44.4	122.7	498
43.0	88.1	567
43.8	132.9	470
Average	102%	530kg/m^3

Table 5 reports the HI AirDry predictions of the MCs (average, core and surface) of the sample boards listed in Table 3 on 24 June (McKay Brighton) and 11 August (NSFP Mowbray). For these predictions, the input variable for initial MC and density are assumed to be the average MC (102%) and average basic density (530 kg/m^3) of the samples reported in Table 4. A mass diffusivity of 1.7x10^{-7} m^2/h was assumed on the basis this is the most common value for 'Tasmanian Oak' species measured in the development of the KILNSCHED program.

Table 5: HI AirDry app predictions of MCs.

Rack ID	Board Width x Thickness (mm)	Time in Yard (days)	HI AirDry app predicted average MC (%)	Measured average MC (%)	HI AirDry app Predicted centre MC (%)	Measured core MC (%)	HI AirDry app predicted surface MC (%)	Measured case MC (%)
54949	100x16	80	19	28.0	19	29.4	19	25.5
54959	100x38	79	36	64.8	45	88.3	26	43.69
54953	100x38	79	34	51.4	44	70.2	25	39.4
54867	150x25	78	18	34.8	18	43.4	18	28.3
54873	150x19	95	18	20.8	18	21.4	18	20.1
54825	125x25	107	18	25.0	18	27.1	18	23.9
02659	150x25	262	23	18.2	22	18.0	25	18.1
02698	125x25	255	21	18.6	21	19.1	23	18.2
02699	125x25	255	23	17.3	23	17.7	23	17.7
44437	125x25	255	21	17.0	21	17.7	22	17.0

All the boards collected from the NSFP Mowbray and the McKay Brighton yard (Tables 1 and 3) with the exception of the two 38mm boards from McKay Brighton had dried close to equilibrium MC by the time they were collected. The two 38m boards (54853 and 54959) were still above fibre saturation point at the time of collection. In order to demonstrate the effect on the HI AirDry predictions of the initial MC, basic density, and mass diffusivity, Table 6 shows the predicted and measured MCs of these boards with an initial MC of 125%, basic density = 637 kg/m^3, mass diffusivity = 1.1x10^{-7} m^2/h and other drying parameters unchanged.

Table 6: HI AirDry app predictions of MCs with initial mc = 125%

Rack ID	Board Width x Thickness (mm)	Time in Yard (days)	HI AirDry app predicted average MC (%)	Measured average MC (%)	HI AirDry app Predicted centre MC (%)	Measured core MC (%)	HI AirDry app predicted surface MC (%)	Measured case MC (%)
54959	100x38	79	54	64.8	75	88.3	31	43.7
54953	100x38	79	51	51.4	70	70.2	30	39.4

Integrating the KILNSCHED model.

For KILNSCHED to generate reliable estimates, it requires information about the rack and its location, the species of timber and variables on external factors that such as climate.

The HI AirDry app includes routines based on informed approximations and other assumptions to moderate sensed data and generate the variables required KILSCHED's effective operation. These seek to account for the differences between yard drying and the controlled environment of kiln-drying. Table 7 lists KILNSCHED's major variable groups, their types and source.

The HI AirDry app requires values of initial moisture content and basic density as the start point for modelling the subsequent drying. Drying yard operations in Tasmania do not currently measure the timber's MC when it is racked out. While not included in the current project, drying estimates could be improved by mills assessing the timber's initial MC and density. Ideally each rack's initial MC could be entered into the HI

AirDry app. In practice, the initial MC of a selection of new racks could be sampled daily. This would require docking a sample from a board in the rack and oven drying overnight to AS1080.1.

Table 7: System variables

Variable groups	Variable type	Notes
Climatic		
Airflow, Temperature, Humidity	Operational	Climate sensing with weather stations and BOM data.
Airflow variables	Programmed	Calculated from CFD modelling and site inputs
Rack characteristics		
Rack species and product	Operational	Site collected with mobile data entry methods. This includes: species, board width; board thickness; board type (quartersawn or backsawn)
Rack location	Operational	Site collected with mobile data entry methods
Species characteristics		
Density and initial MC	Programmed	Determined by species and potentially site collection. This includes: basic density; mass diffusion coefficient.
Drying profile	Programmed	Determined by species. This includes: FSP moisture content.
Shrinkage rates	Programmed	Determined by species. This includes: shrinkage to FSP; equilibrium moisture content (EMC) shrinkage.

System Application development

This stage included the design and development of the prototype HI AirDry application and testing its operational components. This involved:

- Establishing the data structure
- Developing and testing process for operational data collection.
- Configuring systems to working application.

As assembled, the app provided an integrated system available to participant user organisations through web-based interfaces. Its database includes system-managed components such as the physical location referencing systems, climate libraries and drying models, and organisation-centred components such as company users, rack and product information and other production variables.

This structure is based on assumptions that participant firms will:

- Be responsible for data entry and management, and equipment maintenance and connectivity relevant to their operations.
- Require that their data is treated as commercial-in-confidence, and not available to any third party.
- Support a fee-for-service system that provides the computer capacity and infrastructure necessary to operations of its major mechanism.

Results

Data structure

The application's data structure was design to reflect the specialist requirements of hardwood processing and drying. Its databases include system-managed components such as the physical location, climate and drying models, and organisation-centred components such as company users, rack and product information and other production variables. See Figure 25.

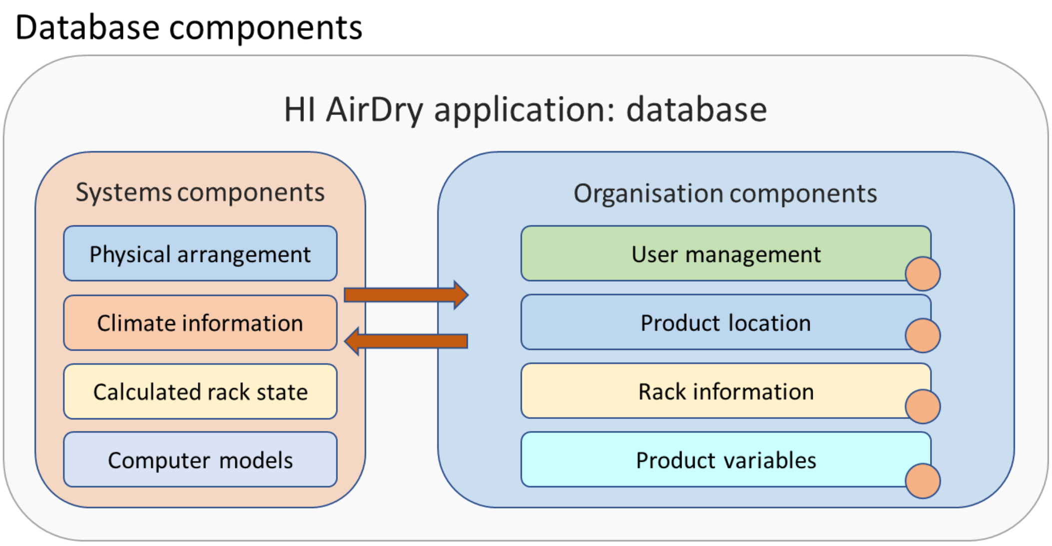


Figure 25: Application system structure

Testing operational data collection

Testing operational data collection involved:

- Configuration of weather stations on site and integration of the data stream into the app. See Figure 9 and Figure 10.
- Confirming yard configuration and row identification.
- Trialling mobile data entry.

Yard configuration and row identification

As discussed above, the HI AirDry application's drying model uses estimated environmental conditions at the rack's location as an input variable. To align rack's virtual location in the application with its actual location in the drying yard, collaborator's rack location processes were reviewed, and revised and refined as necessary. For this:

- Row location and numbers were reconciled with the drone survey and a consistent means of identifying zones and rack locations on site was established. These were documented into row number plan for each yard . See Figure 26.
- Inconsistencies in numbering and row markers were resolved and row marker was reconditioned as required to ensure that the number was clearly legible from the forklift.
- Forklift operators and other yard staff were provided with a copy of the plan and used it during the mobile data entry trial.

Generally, rows were separated into three sections: the middle of the row; and two end sections of normally three stacks. Each end section was identified with features of one side of the site or the other. For example, in Figure 26, the top of the drawing is known as the Quarry side, while the bottom of the drawing is the Council side.

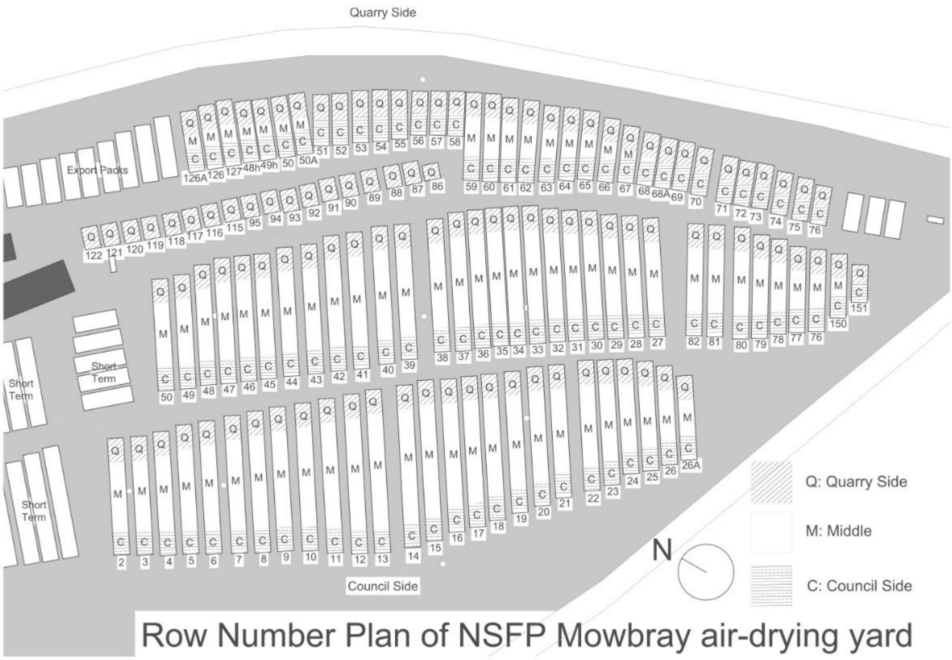


Figure 26: Row number plan for the NSFP yard

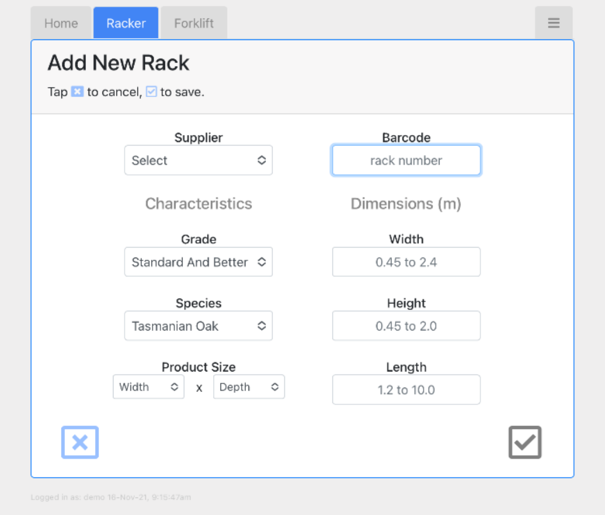
Mobile data entry

A mobile data entry program was developed and operated on a network-enable mobile tablet to allow forklift operators and other yard staff to record rack characteristics and locational information in real time. Table 8 lists the program's field interfaces while Figure 27 shows example screens.

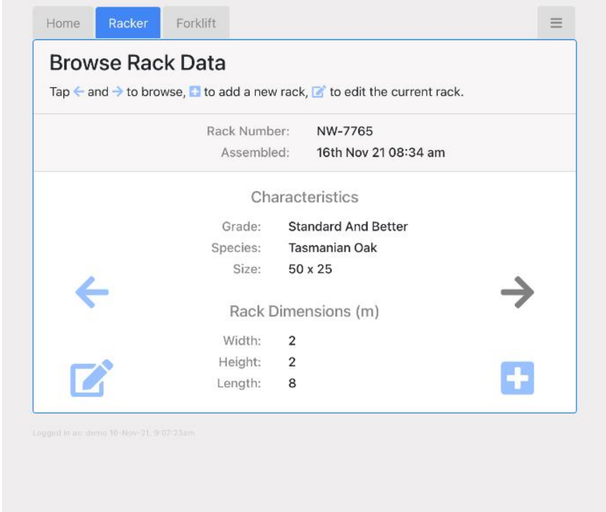
After initial industry review, operational trials of the mobile data entry processes occurred with yard staff at NSFP Mowbray, McKay Timbers' Brighton, and Porta Moulding Bridgewater. Figure 28 shows the project iPads in use, while Table 9 list the trial dates and the number of operational racks entered into the HI AirDry app during the trial period. Operational staff feedback was positive, and the data integrity was encouraging.

Table 8: Field interfaces

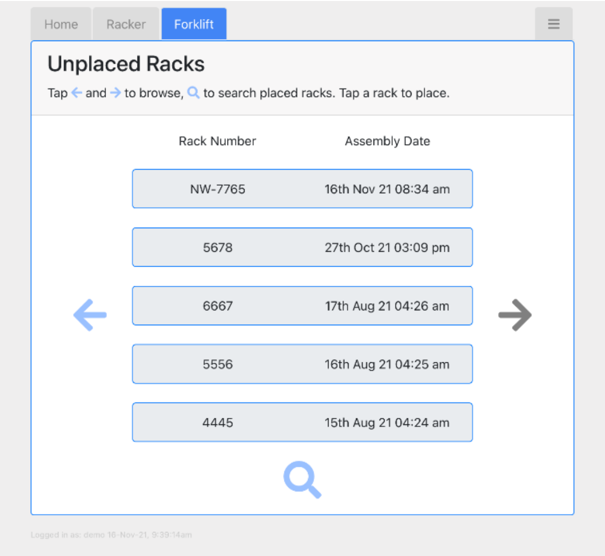
Interface area	General inclusions
Rack creation	Rack number, size, species, grade, product dimensions, and date.
Browse rack	Review and correct information on the rack's characteristics and location.
Rack placement	Rack number, drying location, position in stack, and drying stage, date. This covers the first and subsequent placements and progression of racks to the next production stage.
Rack state	Site measure of rack MC, and other notes on its condition.



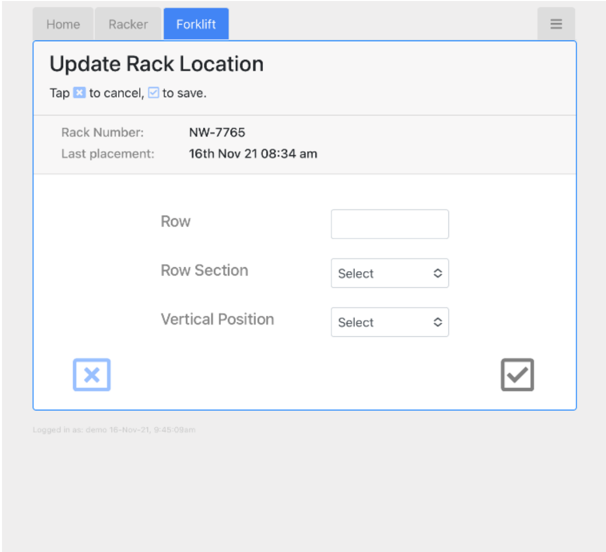
Rack creation



Browse rack



List racks for placement



Place racks

Figure 27: Example screens from the mobile data collection facility

Figure 28: Data entry trial at NSFP Mowbray.

Table 9: Data entry trials

Drying yard	No. racks entered	Trial dates
NSFP Mowbray	255	November 18 to December 17 2021
McKay Timber Brighton	256	March 9 to April 29 2022
Porta Mouldings Bridgewater	160	March 23 to May 22 2022

Application overview

The HI AirDry application was developed and is now operational on a pilot scale on a Nectar research server. Its general configuration is shown in Figure 29. The application estimates the moisture content (MC) and maximum drying stress level in boards within a rack at a recorded position within a drying yard and presents this to drying managers. The app includes *operations*, *systems computer* and *management* components.

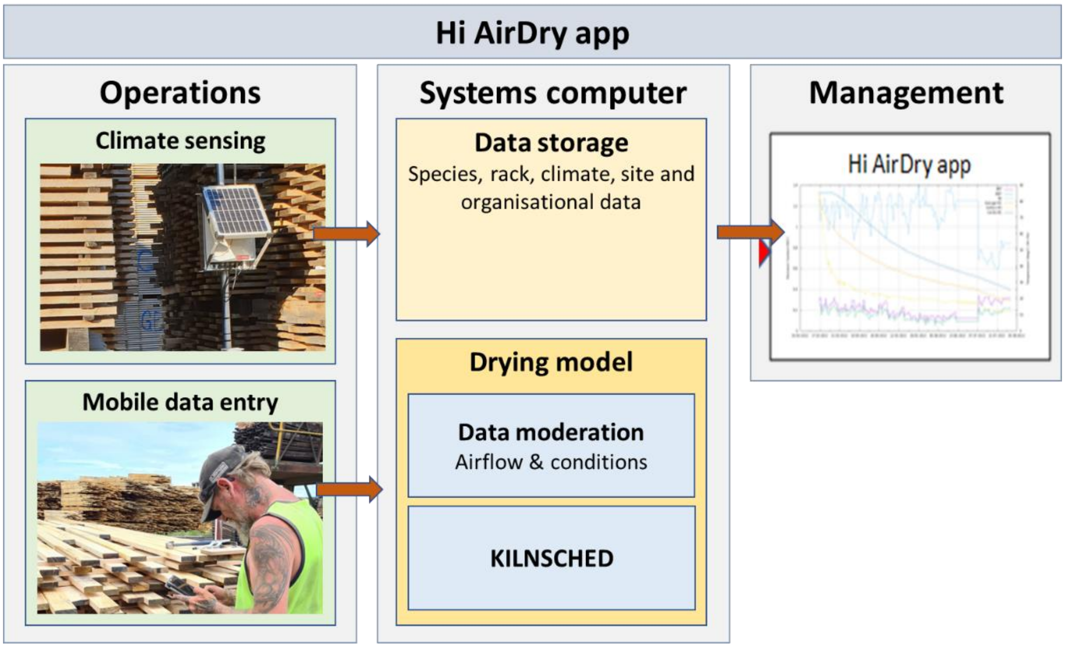


Figure 29: The HI AirDry app general components

Operations components

The *operations* components collect the operational and climate data necessary to identify the characteristics, location and climate conditions that influence the timber's drying. It includes:

- Climate sensing: A weather station at the drying yard collects climate information and streams it into the application's systems computer data storage.
- Mobile data entry: This is a web-based information interface that allows forklift drivers and others to record rack characteristics and location in real time on network-enable mobile tablet.

Systems computer components

The major parts of the *systems computer* component are: data storage and the drying model. The data storage accepts and stores the species, rack, climate, site, organisational and drying information necessary for the application to operate efficiently.

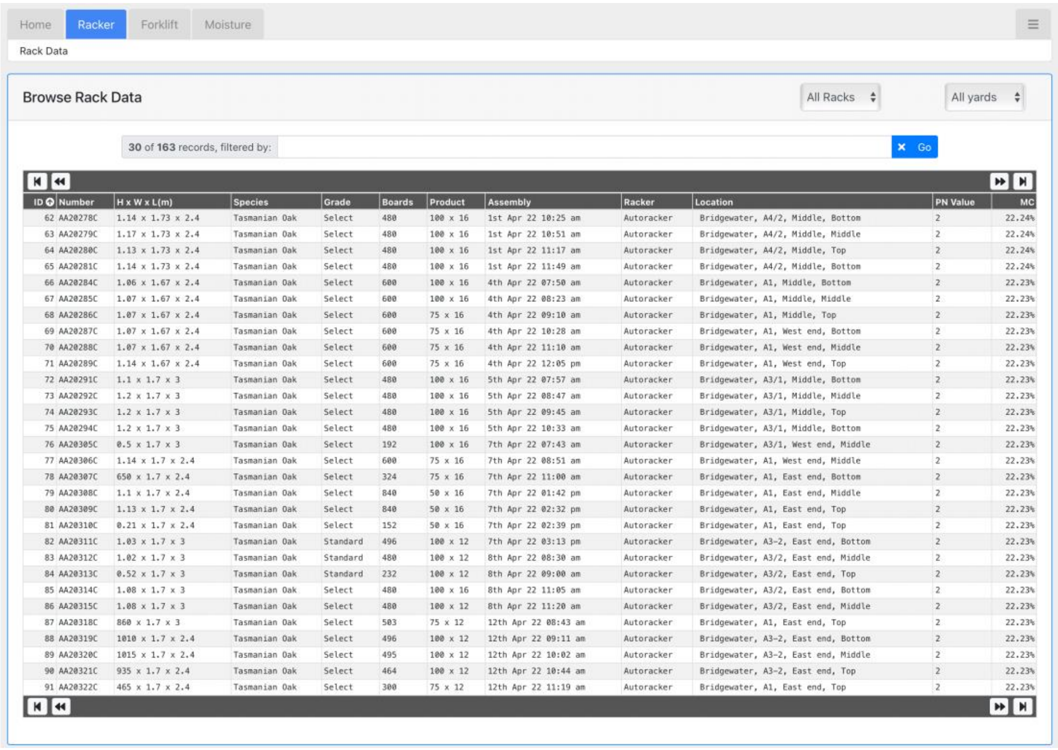
The drying model include the KILNSCHED drying program and a series of data moderation operations refined during the project to prepare the variables required in KILNSCHED. At regular intervals, KILNSCHED uses averaged weather data and runs for each rack in the yard, and generates progressive estimates of the MC and the stress/strain at the surface or in the centre of a board in the rack.

Management component

The *management* component is a web-based interface that allows drying yard manager to view the estimated progression of rack drying and receive warnings if they are liable to degrade under the sensed conditions. The system has the capacity to identify groups of material available for further processing, or at risk of significant drying degrade. The app allows for data import or export to other commercial stock management programs.

The figures below show the pilot application's general operation using rack information entered as part of an industry data entry trial.

- Figure 30 shows the rack data for a yard by rack number and other key variables.
- Figure 31 shows the drying progression of an individual rack in the yard.
  - When the system is operational, estimates would be updated at a set interval and could benchmarked against actual MC readings taken from the rack. Currently, estimates are calculated daily.
  - When the rack is removed from the yard for further processing, the estimate is retained for later assessment.
- Figure 32 shows means for selecting the climate and sensor settings to be used in the KILNSHED estimate.
- Figure 33 shows means for editing key species defaults, such as mass diffusivity.



ID	Number	H x W x L(m)	Species	Grade	Boards	Product	Assembly	Racker	Location	PN Value	MC
62	AA20278C	1.14 x 1.73 x 2.4	Tasmanian Oak	Select	480	100 x 16	1st Apr 22 10:25 am	Autoracker	Bridgewater, A4/2, Middle, Bottom	2	22.24%
63	AA20279C	1.17 x 1.73 x 2.4	Tasmanian Oak	Select	480	100 x 16	1st Apr 22 10:51 am	Autoracker	Bridgewater, A4/2, Middle, Middle	2	22.24%
64	AA20280C	1.13 x 1.73 x 2.4	Tasmanian Oak	Select	480	100 x 16	1st Apr 22 11:17 am	Autoracker	Bridgewater, A4/2, Middle, Top	2	22.24%
65	AA20281C	1.14 x 1.73 x 2.4	Tasmanian Oak	Select	480	100 x 16	1st Apr 22 11:49 am	Autoracker	Bridgewater, A4/2, Middle, Bottom	2	22.24%
66	AA20284C	1.06 x 1.67 x 2.4	Tasmanian Oak	Select	600	100 x 16	4th Apr 22 07:50 am	Autoracker	Bridgewater, A1, Middle, Bottom	2	22.23%
67	AA20285C	1.07 x 1.67 x 2.4	Tasmanian Oak	Select	600	100 x 16	4th Apr 22 08:23 am	Autoracker	Bridgewater, A1, Middle, Middle	2	22.23%
68	AA20286C	1.07 x 1.67 x 2.4	Tasmanian Oak	Select	600	75 x 16	4th Apr 22 09:10 am	Autoracker	Bridgewater, A1, Middle, Top	2	22.23%
69	AA20287C	1.07 x 1.67 x 2.4	Tasmanian Oak	Select	600	75 x 16	4th Apr 22 10:28 am	Autoracker	Bridgewater, A1, West end, Bottom	2	22.23%
70	AA20288C	1.07 x 1.67 x 2.4	Tasmanian Oak	Select	600	75 x 16	4th Apr 22 11:10 am	Autoracker	Bridgewater, A1, West end, Middle	2	22.23%
71	AA20289C	1.14 x 1.67 x 2.4	Tasmanian Oak	Select	600	75 x 16	4th Apr 22 12:05 pm	Autoracker	Bridgewater, A1, West end, Top	2	22.23%
72	AA20291C	1.1 x 1.7 x 3	Tasmanian Oak	Select	480	100 x 16	5th Apr 22 07:57 am	Autoracker	Bridgewater, A3/1, Middle, Bottom	2	22.23%
73	AA20292C	1.2 x 1.7 x 3	Tasmanian Oak	Select	480	100 x 16	5th Apr 22 08:47 am	Autoracker	Bridgewater, A3/1, Middle, Middle	2	22.23%
74	AA20293C	1.2 x 1.7 x 3	Tasmanian Oak	Select	480	100 x 16	5th Apr 22 09:45 am	Autoracker	Bridgewater, A3/1, Middle, Top	2	22.23%
75	AA20294C	1.2 x 1.7 x 3	Tasmanian Oak	Select	480	100 x 16	5th Apr 22 10:33 am	Autoracker	Bridgewater, A3/1, Middle, Bottom	2	22.23%
76	AA20305C	0.5 x 1.7 x 3	Tasmanian Oak	Select	192	100 x 16	7th Apr 22 07:43 am	Autoracker	Bridgewater, A3/1, West end, Middle	2	22.23%
77	AA20306C	1.14 x 1.7 x 2.4	Tasmanian Oak	Select	600	75 x 16	7th Apr 22 08:51 am	Autoracker	Bridgewater, A1, West end, Middle	2	22.23%
78	AA20307C	650 x 1.7 x 2.4	Tasmanian Oak	Select	324	75 x 16	7th Apr 22 11:00 am	Autoracker	Bridgewater, A1, East end, Bottom	2	22.23%
79	AA20308C	1.1 x 1.7 x 2.4	Tasmanian Oak	Select	840	50 x 16	7th Apr 22 01:42 pm	Autoracker	Bridgewater, A1, East end, Middle	2	22.23%
80	AA20309C	1.13 x 1.7 x 2.4	Tasmanian Oak	Select	840	50 x 16	7th Apr 22 02:32 pm	Autoracker	Bridgewater, A1, East end, Top	2	22.23%
81	AA20310C	0.21 x 1.7 x 2.4	Tasmanian Oak	Select	152	50 x 16	7th Apr 22 02:39 pm	Autoracker	Bridgewater, A1, East end, Top	2	22.23%
82	AA20311C	1.03 x 1.7 x 3	Tasmanian Oak	Standard	496	100 x 12	7th Apr 22 03:13 pm	Autoracker	Bridgewater, A3-2, East end, Bottom	2	22.23%
83	AA20312C	1.02 x 1.7 x 3	Tasmanian Oak	Standard	480	100 x 12	8th Apr 22 08:30 am	Autoracker	Bridgewater, A3/2, East end, Middle	2	22.23%
84	AA20313C	0.52 x 1.7 x 3	Tasmanian Oak	Standard	232	100 x 12	8th Apr 22 09:00 am	Autoracker	Bridgewater, A3/2, East end, Top	2	22.23%
85	AA20314C	1.08 x 1.7 x 3	Tasmanian Oak	Select	480	100 x 16	8th Apr 22 11:05 am	Autoracker	Bridgewater, A3/2, East end, Bottom	2	22.23%
86	AA20315C	1.08 x 1.7 x 3	Tasmanian Oak	Select	480	100 x 12	8th Apr 22 11:20 am	Autoracker	Bridgewater, A3/2, East end, Middle	2	22.23%
87	AA20318C	860 x 1.7 x 3	Tasmanian Oak	Select	503	75 x 12	12th Apr 22 08:43 am	Autoracker	Bridgewater, A1, East end, Top	2	22.23%
88	AA20319C	1010 x 1.7 x 2.4	Tasmanian Oak	Select	496	100 x 12	12th Apr 22 09:11 am	Autoracker	Bridgewater, A3-2, East end, Bottom	2	22.23%
89	AA20320C	1015 x 1.7 x 2.4	Tasmanian Oak	Select	495	100 x 12	12th Apr 22 10:02 am	Autoracker	Bridgewater, A3-2, East end, Middle	2	22.23%
90	AA20321C	935 x 1.7 x 2.4	Tasmanian Oak	Select	464	100 x 12	12th Apr 22 10:44 am	Autoracker	Bridgewater, A3-2, East end, Top	2	22.23%
91	AA20322C	465 x 1.7 x 2.4	Tasmanian Oak	Select	300	75 x 12	12th Apr 22 11:19 am	Autoracker	Bridgewater, A1, East end, Top	2	22.23%

Figure 30: The HI AirDry app's estimation of drying for a single rack.

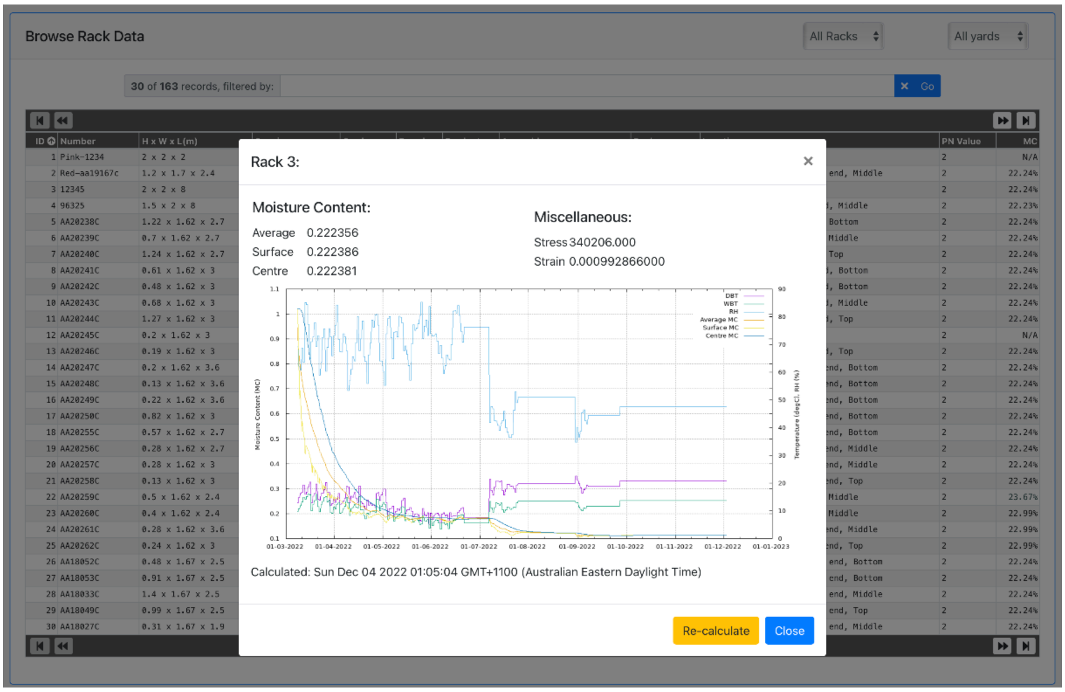


Figure 31: HI AirDry app: Drying estimate for a single rack.

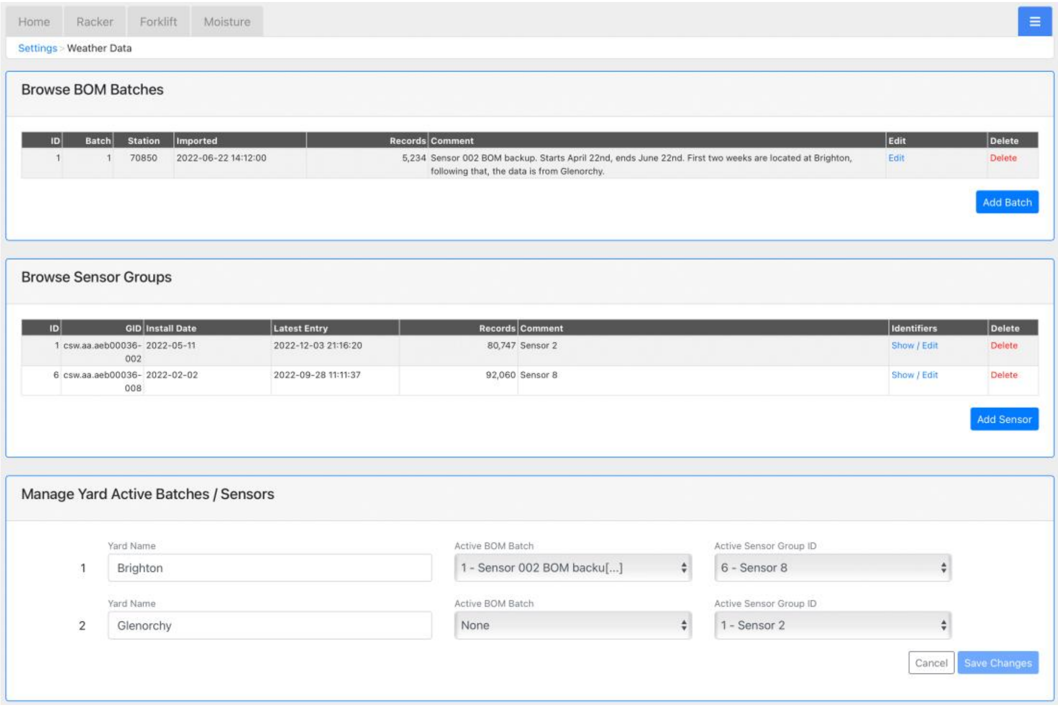


Figure 32: HI AirDry app: Setting climate and sensor defaults.

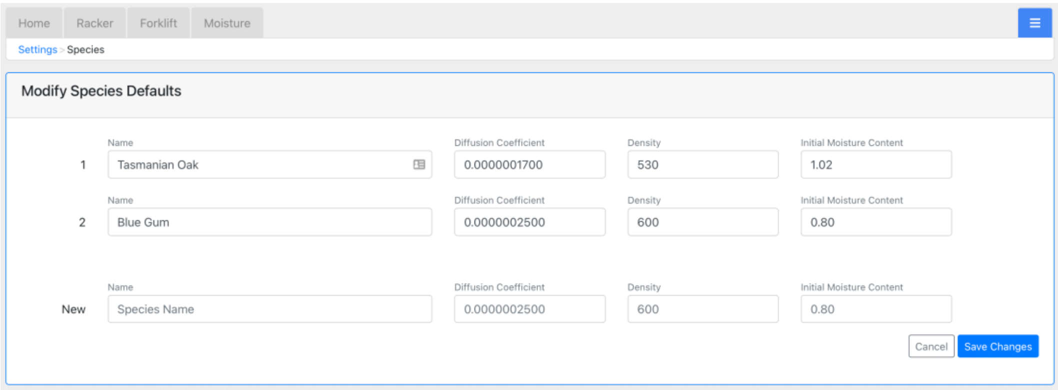


Figure 33: HI AirDry app: Setting species defaults

Industry adoption

Industry has been active in the systems development, particularly during yard trial. Industry briefing were held in Hobart, Launceston and online in March 2022.

Also, each drying yard was visited in June-July 2022 and drying staff were shown the CFD results for their site and consulted on their experience with local airflow and drying patterns. Sets of interpreted CFD results for each site were distributed.

Conclusion

This project aimed to develop and validate a timber drying technology suite with an accompanying decision-making support tool, the Hardwood Improved Air Drying (HI AirDry) application for higher value product recovery across the wider hardwood Industry. This required

- Expansion of material and site information base to increase the accuracy and flexibility in the computer drying model.
- Development of the mechanisms required to reliably generate useful estimates of the drying condition at yard locations and the progressive drying of boards in rack given those conditions
- The design and development of the prototype HI AirDry application and testing its operational components.
- Communicating the results,

The benefits of CFD modelling were investigated. Currently, the principal benefit of CFD site modelling appears to be as a heuristic indicator of stack locations susceptible to rapid or slow drying rather than, as originally intended, as direct input to the KILNSCHED model. Given these results, two factors were incorporated into the system to allow for abnormal yard drying. Initial validation indicates that this may be a useful approach. Dynamic PN assignment using CFD results was also assessed and may be viable with further development.

The HI AirDry application was developed and is now operational on a pilot scale on a Nectar research server. The application estimates the moisture content (MC) and maximum drying stress level in boards within a rack at a recorded position within a drying yard and presents this to drying managers in a web-accessible form.

Several areas of further development will improve drying estimates.

- Hi AirDry app uses assigned PN values to identify positions in a yard at which racks are expected to dry slower or faster than average. These are determined by a combination of inspection of the CFD modelling results and the experience of yard managers of historical drying behaviour. If the Hi AirDry app is to be used commercially, it should incorporate a system for automatically determining PN values from a minimum of drone surveys and CFD modelling. Dynamic PN assignment using CFD results was also assessed but requires additional development.
- The Hi Airdry app's predictions of moisture content are very sensitive to the initial moisture content of the timber when racked and positioned in the drying yard. For the app to give useful predictions of moisture content and stress levels, there needs to be a process for measuring and building a better understanding of initial moisture content.
- Additional structured validation runs are required at nominally 2 mills. This would involve deployment of the mobile data units, entry of normal production information into the HI AirDry app, and MC assessment of rack drying in several locations with sample boards.
- The value of key drying variables such as mass diffusivity could be updated or refined to reflect the current milling resource, particularly the increased supply of younger native and plantation logs.

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Salin, J. G. (2011). Fibre level modelling of free water behaviour during wood drying and wetting. Maderas. Ciencia y tecnología,13(2), 153-162.