PREDICTIVE CONTROL FOR KILN DRYING LUMBER

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Control of Lumber Dry Kilns

Traditional

- Conventional open loop control of lumber drying:
  - control kiln atmosphere temperature and humidity to predefined schedules actuating heating valves and vents.
- Manual "closed loop" control:
  - monitor the drying outcome and refine the drying schedule
  - periodically extract sample boards to assess the drying rate and adjust the drying schedule.
- Decades ago this was adequate
  - mills drew logs from a few geo-climatic zones and the lumber properties were relatively consistent and known.
- Today logs are widely traded between mills and kiln charges are more variable. Manual tuning of the controls cannot cope with the throughput rate.

Modern

- High volume dimension lumber drying has short, high temperature drying cycles, no time to use sample boards.
  - The skill level of kiln operators is variable and turnover high; manual adjustments to drying schedules "on the fly" require seasoned judgment and errors are expensive.
- Modern kiln controls automate closed loop control, using in kiln sensors (MC, etc.) and quasi-empirical algorithms.
  - May adaptively delay schedule transitions until desired MC or drying rate achieved.
- State-of-the-art control systems employ several sensors, sometimes in combination:
  - Resistance probes monitoring the moisture content (MC) of a set of sample boards.
  - Dual resistance probes monitoring MC gradient.
  - Temperature difference across the load as a measure of aggregate drying rate.
  - Kiln load weight measurement.
- Limitation: assumes the load is more or less homogeneous, vulnerable to bias in sample board selection.

Advanced

- Using sensors to characterize the variability of lumber MC and drying characteristics and kiln drying conditions:

- IR monitoring of 2-dimensional MC &/or drying rate on the load face.
- Ultrasonic or stress wave M.C. measurement
- CAT scan
- Acoustic emission monitoring (lumber cracking).

- None have been reduced to practice
- Nothing today directly controls the drying rates & MC gradients that cause degrade.

Intelligent

- Model based control can generate "virtual" measures of MC gradients & stress for closed loop control.
- Intelligent lumber dry kiln control takes a systems approach responsive to measured drying performance (adaptive control)
  - Based on general and detailed models of the drying process.

VOC Mitigation

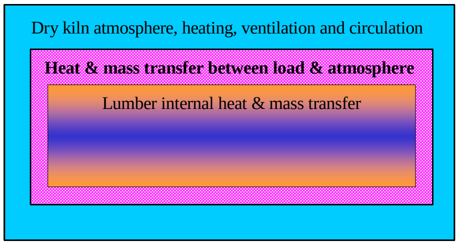
- Lumber dry kilns emit volatile organic compounds (VOC) that are "hazardous atmospheric pollutants" (HAP) subject to regulation
- Lumber drying control systems that minimize VOC emissions with adaptive control may be a cost effective response.
- Combining drying & VOC control requires a complex system with interacting control loops, multiple modes of operation (for different drying phases) and many constraints.
- Defining the optimal control solution for a wide range of drying conditions is difficult.

Model Based Monitoring and Control

- Model based control uses models of physical processes to create virtual sensors for closed loop control (e.g., drying rate, MC gradient, stress levels)
- Models can dynamically adjust control loop parameters for more precise drying control, improving drying quality.
- Model based control facilitates the use of multiple sensors and effectors (multiple input/multiple output, MIMO) to achieve optimal performance: e.g., combined circulation fan speed, temperature and humidity control for best cycle time, quality and energy consumption.
- Models can flag process deviations for fault identification and isolation
  - Depend on the fidelity of the models, and must accommodate variation of equipment performance or kiln charge characteristics.
- Advanced techniques tune the process model(s) to account for performance degradation and feedstock variation.
  - Practical experience with these techniques is limited.
  - Realistic models of variation & degradation are critical.
  - Knowing where to draw the limit to adaptive control and validation for actual use remain challenging.

Conceptual Approach to Modeling Kiln Drying

- At some level, kiln control is based on models of these processes.



Wood Drying Models – Internal Heat & Mass Transfer, & Strain

- Modeling the internal drying of wood considers two processes:
    - the migration of water & moisture content gradients
    - the strains imposed by differential wood shrinkage
- VOC emission processes are likely similar to drying, possibly with some influence of water transport and chemical reactions.

Wood Drying Models - Internal
- Finite element analysis to simulate combined drying and wood stress is too complex, inapplicable for control.
- Simpler drying models - theoretical, empirical, or mixed - can be used for integrated kiln drying control.
- Wood stresses are derived from the drying models' moisture gradient evolution.
- Releases of VOC could also be similarly modeled, requires measurement & understanding of the basic physical processes.

Wood Drying Models – Kiln Charge
- Detail modeling of real kiln charges is impractical
    - highly variable wood properties
    - need measurements of individual board characteristics (density, MC, grain orientation)
- Semi-empirical constraints and simple models of wood drying provide the basis for constraints for high-level model based control.
- Similar parametric models for VOC release should be practical.

External Heat & Mass Transfer
- More tractable for theoretical & semi-empirical treatment. Well validated models exist.
- Variation in board size, stacking & stickering and kiln airflow & temperature distribution limits model fidelity
    - Aggregate and approximate charge characterization
- Empirical and semi-theoretical models combine internal and external heat & mass transfer effectively
- A similar approach may suffice for VOC emissions prediction

Integrated Lumber Dry Kiln Modeling
- A "one-dimensional" model of the overall process
    - Model and characterize aggregate kiln charge heat & mass transfer.
    - Models for circulation, heating, steaming and spraying, ventilation and control system dynamics are available to be customized to the kiln design.

- Two- or three-dimensional models of the kiln airflow and kiln charge can also be developed to represent airflow and heat & mass transfer in more detail.
- To characterize the kiln and load behavior for control logic design.
- A suite of models for heat & mass transfer between atmosphere & load and within the load, and the resulting stresses

Complex Control Logic and Architectures

- Complex control systems (multi-input/multi-output, conventional or model based) are difficult to implement, with hard to predict interactions.
  - Extensive analysis & testing is required
  - Minor changes = extensive code rewrite and test.
- Comprehension of the total process and control system interactions becomes the limiting factor for design

Advanced Control Techniques

- "Fuzzy logic" and neural nets have shown promise to manage the high variability of natural resource feed stocks.
  - Fuzzy logic is ill adapted to control constraints.
  - Neural nets need extensive "training".
- Application of these techniques to drying has promise, and may have application to combine quality drying with VOC control:
  - E.g., a neural net model to predict both lumber stress and VOC release from drying parameters.

Model Predictive Control

- Model predictive control (MPC) is a radical departure
  - Applied today to process control, particularly in Europe.
- Theoretical concepts date to the '60s, application primarily to petroleum refining and petrochemicals processing.
  - Application to pulp digesting is growing.
  - Wood chip & OSB strand drying control is in use.
  - The University of Sydney (Australia) has demonstrated a 10% reduction in hardwood timber drying time using MPC.

Modern predictive control - defined

- MPC defines a path in "state space" to achieve a desired end state while optimally satisfying an objective function:
  - A trade off of measured or virtual process parameters
  - Includes both engineering and economic metrics.
- MPC recursively optimizes the solution within a finite time interval, the prediction horizon.
- Based on an integrated model of the process
  - vs. conventional control logic with multiple control loops for each process input/output, with dedicated sensors.
- State-of-the-art MPC uses linearized models
  - Formulations for non-linear models are coming.

- Requires a representative & stable process model
  - "Process identification" techniques may generate empirical dynamic models from process test data.
- Adaptive models are being developed
  - Tune the process model on-line to variations in behavior, between plants and with degradation over time.

Model Predictive Control Today
- Initially, MPC formulations were proprietary to the industrial users.
- Specialized and general purpose control system suppliers have emerged:
  - Adersa, DMC Corp., Honeywell Profimatics, Setpoint Inc., Trieber Controls, and Matricon offer custom designed MPC and hybrid-MPC control systems and toolsets.
  - Honeywell (RMPCT), ABB (3D-MPC) and Matlab (MPC Toolbox) provide software development environments
- In process control applications, MPC software runs on robust proprietary operating systems or COTS OS (Wind River VxWorks, Green Hills INTEGRITY, Linux/RT…).

MPC & Process Monitoring
- MPC enables real-time monitoring of deviations between the process and the model. MPC's accommodation of these deviations can provide valuable inputs to process monitoring:
  - Track equipment and process performance degradation.
  - Detect and isolate equipment failures.
  - Characterize and adapt to individual kiln charge behavior.

MPC - Advantages
- Optimal control solutions "on the fly" accounting for process constraints and interactions.
- The control logic is updated by modifying the model, constraints or objective function, with less testing, trial & error.
- Additional sensors, effectors and other process changes accommodated with model updates. Process parameters from the models provide "virtual sensors".
- MPC is robust in handling process upsets, loss of sensors or effectors, and operator interventions.
- A well developed body of practice exists within a diverse resource base.

MPC - Challenges
- MPC is unfamiliar and technically daunting
  - MPC is now a part of controls engineering courses.
- Validation/verification procedures are immature.
  - Lumber drying is non-critical and tolerant of moderate process deviations.
- MPC's computational burden is high for complex processes with short time constants.
  - The slow drying process can be accommodated with a PC.
- Reliable, robust and accurate process models are needed.
  - Better drying models that adequately represent lumber drying & VOC generation.

Integrated Control of Drying and VOC Emissions

- Research shows lumber drying and VOC emissions are interdependent. Simple kiln controls are not capable of managing the both processes.
- Conventional multi-input/multi-output (MIMO) solutions will be difficult to develop and impractical to adapt to the large variations in lumber kiln charge characteristics.
- MPC offers a powerful and flexible tool to optimize lumber drying for conflicting requirements with strongly interacting process parameters.
- Adequately modeling lumber drying can be accomplished.
- Basic research and analysis is needed to develop adequate models of VOC generation.
  - The process is ill-understood and the interaction with the drying process ill-defined.
  - Optimal control of drying and VOC's needs better theoretical understanding and empirical data.
- Probabilistic (e.g., "fuzzy logic) approaches should be considered to handle variability within the kiln charge and between kiln loads.
  - Hybrid MPC designs are available.
- MPC is most effective with more inputs than process degrees of freedom. Additional process control inputs would widen the scope for precision control and process monitoring:
  - Variable speed fans & airflow distribution control
  - Steaming and spraying, dehumidification
  - M.C. & species sorting, better characterizing of the load
  - Redundant sensors (TDAL, load M.C. distribution, internal lumber M.C. gradients, lumber strain or cracking…).
- Retrofitting existing kilns will require only process controller upgrades.