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Smart Factories: How AI Will Help To Improve Timber Grading?

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Timber is a sustainable and versatile structural material whose value can be maximised through accurate grading. Grading ensures structural reliability, optimises market value, and reduces waste by classifying wood based on strength, durability, and appearance. Traditional methods are divided into visual and machine-based approaches. Visual grading relies on trained assessors but is often subjective and unsuitable for detecting internal flaws. Machine grading using traditional Non-Destructive Testing (NDT) provides objective evaluation but often relies on linear models that fail to capture the biological complexity of wood 3. Artificial Intelligence (AI) has emerged as a transformative solution, integrating with NDT systems to enable species classification, defect detection, and strength prediction with superior speed and accuracy. This document explores AI's role in Industry 4.0, detailing various machine learning pipelines and case studies ranging from mobile wood identification to terahertz imaging for internal defect characterisation.

Keywords: Artificial Intelligence, Timber Grading, Industry 4.0, Non-Destructive Testing, Deep Learning.

Introduction

Forests serve as vital carbon reservoirs and biodiversity hotspots, providing wood as one of humanity's oldest and most adaptable raw materials. The timber industry transforms harvested logs into semi-finished and finished products used in infrastructure, furniture, and engineered wood applications. A critical step in this processing flow is timber grading, which categorises wood based on its inherent characteristics. Figure 1: Flowchart of Timber Processing from Forest to End Use illustrates the journey of wood from forest harvesting and debarking to the final conversion into sawn or veneer timber. Accurate grading ensures that wood is used for the right purpose, balancing strength and aesthetic requirements to maximise resource efficiency and structural safety. This flowchart shows how logs move through debarking, sorting, and conversion into lumber or plywood for construction and furniture industries.

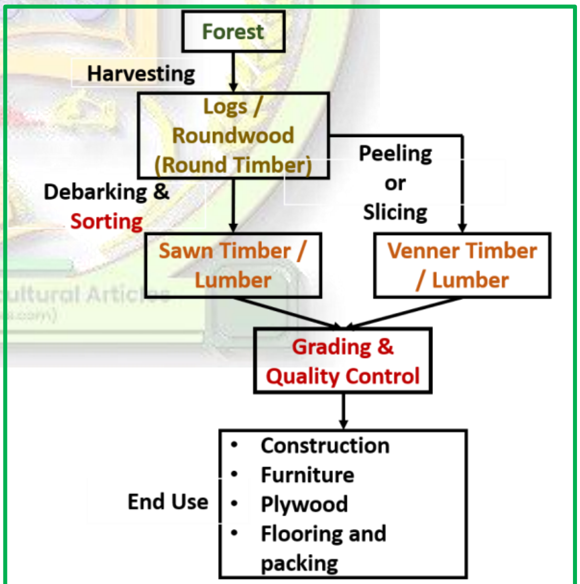

Fig. 1: Flowchart of Timber Processing from Forest to End Use

Background of Timber Grading

Timber grading methods are broadly classified into visual (manual) and machine-based (instrumental) techniques. Visual grading involves a human expert inspecting wood surfaces to identify species, measure dimensions, and examine parameters like knots, cracks, and grain slope. It is a foundational method used for both aesthetic and structural classification. Machine grading, which became commercially available in the 1960s, utilizes sensors for Non-Destructive Testing (NDT) to evaluate mechanical properties without damaging the sample. Key parameters assessed include density, stiffness, and the modulus of elasticity (MOE). Modern machine grading is increasingly aligned with Industry 4.0 frameworks, emphasizing data-driven automation and real-time quality control.

Table 1: Overview of available NDT methods for wood

Parameters / Material State	Methods
Modulus of elasticity	Ultrasound
Density	Ultrasound, X-ray, Microwave, Resonance (NMR), Drilling, Electromagnetic methods
Moisture	X-ray, Microwave, Resonance (NMR), Electromagnetic methods
Layer thickness measurement	Optical, Electromagnetic methods
Inhomogeneity	Ultrasound, Acoustic emission, X-ray, Microwave, Resonance (NMR), Electromagnetic methods, Thermography, Microwave, Visual inspection
Cracks	Ultrasound, Acoustic emission, X-ray, Thermography, Visual inspection
Decay	Ultrasound, X-ray, Thermography, Visual inspection
Failure	Acoustic emission, Thermography
Deformations	Optical laser, Acoustic emission, Visual inspection
Stiffness	Ultrasound

Non-Destructive Testing (NDT) Methods

Table 1: Overview of available NDT methods for wood identifies the primary technologies used to assess timber propertie. Ultrasound and resonance techniques are used to measure the modulus of elasticity, while X-ray, microwave, and electromagnetic methods assess density and moisture content. Optical and electromagnetic sensors are typically employed for layer thickness measurements, and thermography is used to detect internal inhomogeneities. These NDT methods provide the raw data required for objective assessment, but their effectiveness depends heavily on the accuracy of the mathematical models used to interpret the signals.

The Evolution of Machine Grading

Machine-stress-rating (MSR) systems originally used mechanical bending to measure stiffness directly. Contemporary systems have evolved to include acoustic and vibration-based assessments, which are faster and more consistent than manual methods. These systems are essential for high-throughput industrial environments where human graders would suffer from fatigue. Furthermore, machine grading allows for digital documentation and traceability, which are core requirements for modern supply chain management and standardized construction practices.

Problem Statement: Limitations of Traditional Methods

Traditional visual grading suffers from significant drawbacks, including subjectivity, inconsistency, and low accuracy in predicting structural strength. Human error is common, and experts can be misled by surface appearances that do not reflect internal structural integrity. Manual inspection is also labor-intensive and fails to provide the digital data needed for Industry 4.0 integration. Figure 2: Linear regressions between static MOEm and NDT parameters demonstrates the limitations of traditional linear modeling. The decision coefficients (R^2) for predicting mechanical properties using acoustic and vibration methods often hover around 0.5, indicating only moderate correlation.

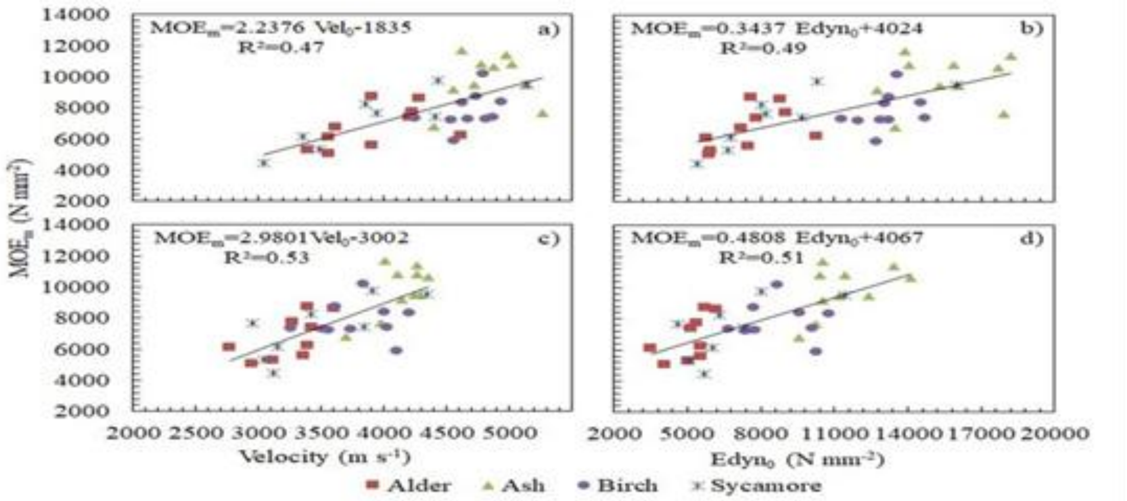

Fig. 3: Linear regressions between static MOEm and (a) TreeSonic velocity, (b) TreeSonic Edyn0, (c) MTG velocity, and (d) MTG Edyn0 (Adopted from Llana et al., 2020)

The Challenge of Wood's Complexity

Wood is a highly heterogeneous biological material with significant variation between species and even within a single log. Traditional linear regression models often fail to capture the non-linear relationships between NDT signals and actual wood strength. Factors such as moisture content, temperature, and hidden internal defects like decay or sub-surface knots introduce noise that linear models cannot effectively filter. This results in conservative grading, where structurally sound timber is downgraded or wasted because its properties were not accurately predicted.

The Need for AI Integration

The timber industry faces increasing pressure to maximize log utilization and reduce waste while meeting strict safety standards. AI-driven models, particularly deep learning networks, can analyze vast amounts of multi-modal data to detect subtle patterns that human inspectors or simple sensors miss. By modeling complex non-linear relationships, AI can significantly improve the decision-making process in timber grading, providing a scalable and objective framework for quality assessment across the entire wood value chain.

General AI Pipeline for Timber Grading

The transition to AI-driven grading involves a structured machine learning pipeline: data acquisition, preprocessing, feature extraction, model selection, and testing. Data is acquired through industrial imaging (RGB, X-ray, CT) or spectral sensors. Preprocessing standardizes this data through normalization, noise reduction, and image sharpening. Feature extraction uses techniques like Gray-Level Co-occurrence Matrix (GLCM) to quantify grain texture. Deep learning models, specifically Convolutional Neural Networks (CNNs), are often selected for their ability to learn spatial hierarchies directly from images.

Case Studies on AI Applications in Timber Identification, Quality Assessment, and Structural Evaluation

Recent advances in artificial intelligence (AI), deep learning, and non-destructive testing (NDT) have significantly improved timber identification, quality assessment, and structural evaluation. In the field of wood identification, the MyWood-ID system employed smartphone-based imaging with a 20× macro lens and a lightweight SqueezeNet convolutional neural network (CNN) to classify over 100 Malaysian timber species, achieving 77.52% Top-1 accuracy at the species level and 84.04% accuracy at the family level, demonstrating its potential for rapid field identification and illegal logging prevention. For industrial quality control, a two-stage deep learning framework integrating a Neural

Architecture Search (NAS)-based glance network with Mask R-CNN enabled automated veneer defect detection, achieving 98.7% detection accuracy, 95.31% mean average precision (mAP), and 100% crack detection accuracy, thereby outperforming conventional visual inspection systems. To overcome the limitations of conventional non-destructive testing, researchers integrated 100 GHz terahertz (THz) imaging with CNN, U-Net, and YOLOv5 models for internal defect detection. The proposed approach classified defects such as decay and knots with over 96% accuracy, while YOLOv5 localized defects with an F1-score exceeding 0.97 and predicted defect dimensions with an average error of less than 4%. AI has also improved forest inventory management through automated log volume estimation, where an enhanced Mask R-CNN model combined with Res2Net feature extraction and stereo imaging achieved a remarkably low volume estimation error of 0.646%, making it suitable for real-time deployment on embedded systems. Furthermore, AI-based predictive modeling has proven highly effective for assessing the structural integrity of heritage timber. By integrating microdrilling resistance, ultrasonic velocity, and colorimetric data, Relevance Vector Machine (RVM) models accurately predicted wood density, modulus of elasticity (MOE), and compressive strength with R^2 values greater than 0.98, outperforming conventional Multiple Linear Regression (MLR) models and demonstrating AI's ability to model the complex, non-linear properties of aged timber.

Discussion of Model Performance

The findings across all case studies indicate that there is no single "best" model, as the choice depends on the specific industrial context. YOLO models are prioritized for high-speed, real-time defect detection on production lines due to their "one-pass" processing capability. Conversely, R-CNN variants are preferred when high precision in defect segmentation and boundary demarcation is required, even if processing is slightly slower. Hybrid systems that combine traditional machine learning for interpretability and deep learning for feature complexity are becoming increasingly popular.

Industry 4.0 and Smart Factories

Integrating AI into timber grading is a cornerstone of the digital transformation in forestry 63. Smart factories use these systems to enable real-time monitoring, automated quality control, and predictive maintenance of grading equipment. The ability to deliver grading results in standardized formats like JSON or CSV allows for seamless integration with sawmill databases and automated sorting machinery. This connectivity ensures that every piece of timber has a digital twin, enhancing traceability and compliance across the global supply chain.

Conclusion

AI-driven timber grading significantly improves the speed, accuracy, and consistency of wood assessment. By overcoming the subjective limitations of visual grading and the modeling weaknesses of traditional NDT, AI systems provide objective and repeatable results. These technologies maximize log utilization and support sustainable forestry by ensuring structurally sound wood is appropriately identified and utilized. The successful deployment of AI on mobile devices and industrial production lines marks a transformative step toward efficient and transparent wood manufacturing.

Way Forward: Multi-Modal Sensing

The future of timber grading lies in unified, standardized frameworks that generalize across species and regions. A key advancement will be the fusion of multi-modal sensing technologies, integrating RGB, terahertz, near-infrared, and LiDAR data. This "sensor fusion" will allow for the simultaneous detection of surface and internal defects with unprecedented precision. Large-scale digital supply chains will link these systems to unique log IDs, creating end-to-end quality records from the forest floor to the final consumer.

Edge AI and Automation

Research will prioritize energy-efficient "Edge AI" models that can be deployed on UAVs and harvesting equipment. This will enable pre-harvest wood-quality assessment of standing trees through laser scanning and spectral imaging. AI-guided robotic harvesters will eventually perform real-time grading and selective cutting as trees are felled. These developments, aligned with automation and sustainability goals, will redefine the timber industry as a data-driven, high-precision sector.

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