# Research Progress of Finite Element Technology in Wood Processing

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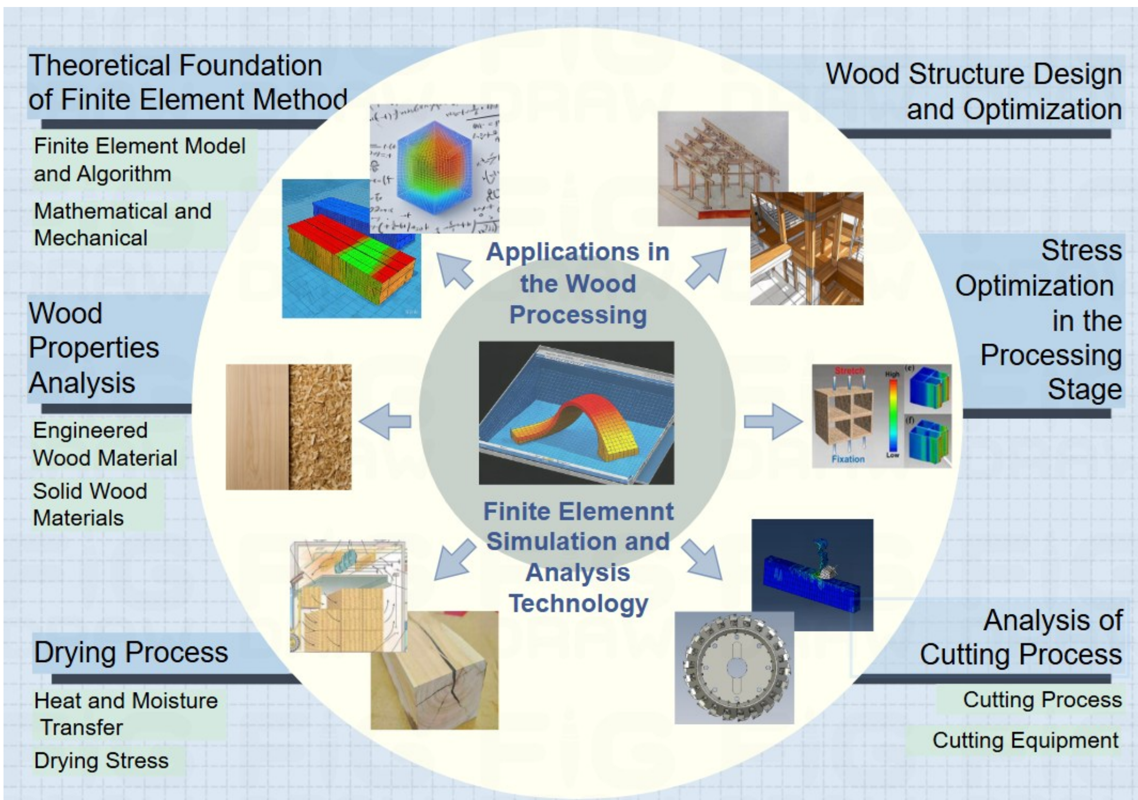
## GRAPHICAL ABSTRACT



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With the development of the wood processing industry toward intelligence, automation, and informatization, Finite Element Analysis(FEA) technology has become increasingly mature in this field. It effectively simulates various aspects, including the properties of wood materials, drying processes, and cutting operations. In material property analysis, FEA technology accurately models the anisotropy and heterogeneity of wood, predicting its mechanical responses under different loading conditions. For drying simulations, it establishes moisture migration models to predict drying stress and reduce defects. In cutting processes, FEA technology analyzes cutting forces, temperature distributions, and surface quality, providing theoretical support for parameter optimization. This review focuses on FEA applications in wood processing, encompassing both solid wood and engineered wood products, simulating and characterizing the drying process of wood products, and modeling cutting operations. It highlights challenges such as model accuracy and algorithm optimization, suggesting that continuous improvements in FEA models and algorithms can further enhance processing efficiency and product quality. Finally, it explores the role of FEA technology in driving innovation and promoting sustainable development in wood processing.

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## INTRODUCTION

With the global manufacturing industry gradually transitioning toward intelligent, standardized, and specialized development, under the strategic framework of "Made in China 2025," the wood processing industry urgently requires technological upgrades to reduce processing costs and enhance efficiency (Mayencourt and Mueller 2019; Tretyakova *et al.* 2021). Finite Element Analysis (FEA), a numerical analysis method capable of solving practical problems across various engineering fields, partitions an object's overall volume or region into multiple smaller, interconnected sub-regions. This characteristic allows enterprises to simulate complex real-world physical processing scenarios at a relatively low cost, enabling the derivation of accurate conclusions for practical applications (He *et al.* 2020; Alade and Ibrahim 2022; Liu *et al.* 2023). These conclusions encompass predictions of processing outcomes, simulations of material properties and parameters, and analyses of structural mechanical characteristics.

Wood, being a lignocellulosic biomass material (Li *et al*. 2007), exhibits fundamental differences in FEA complexity compared to non-wood materials such as metals and plastics. The homogeneity and isotropic properties of metals and plastics simplify modeling – for instance, aluminum alloys typically show yield strength variations below 5%, with thermo-mechanical coupling models sufficiently addressing most engineering requirements through dominant thermal expansion responses (Aboussafy and Guilbault 2021). However, wood's strong anisotropy and microstructural heterogeneity significantly increase modeling challenges: longitudinal elastic modulus can be 20 times greater than transverse values, while density differences between earlywood and latewood exceed 30% (Kiraly *et al.* 2023). Additionally, wood's hygroscopic nature creates moisture-dependent mechanical behavior, requiring simultaneous solutions of moisture diffusion and mechanical equilibrium equations (Zhou *et al.* 2020). This multiphysics coupling results in substantially higher computational complexity for wood drying simulations compared to metal forming. For example, Zhou *et al.*'s (2020) eucalyptus drying model required tens of millions of elements and days of iteration, whereas comparable metal stamping simulations complete in tens of minutes.

In industrial applications, metal FEA focuses on pushing performance limits (*e.g.*, fatigue life optimization for aerospace alloys), while wood processing prioritizes defect mitigation and resource efficiency. This includes humidity gradient simulations to reduce drying cracks (Redman *et al.* 2018) or designing sawtooth geometries aligned with fiber orientation to minimize blade chipping (Warguła *et al.* 2023).

Technologically, non-wood material FEA emphasizes physical simplification and computational efficiency, exemplified by GPU-accelerated metal forming simulations (LS-DYNA R12) achieving 10,000-core parallel computing. Wood simulations are evolving toward bio-intelligent modeling, integrating CT scanning with deep learning for microstructural reconstruction (Zeng *et al.* 2024), or machine learning-based calibration of constitutive parameters (Liu *et al.* 2023). This multiscale integration not only enhances predictive accuracy, but it also drives sustainable innovations such as low-energy drying (40% reduction) and waste-derived composite development. These material-specific differences reflect an FEA paradigm shift from "homogeneous physics-driven" to "bio-physical synergy-driven" approaches, demonstrating material science diversity while establishing new cross-disciplinary theoretical frameworks.

As a versatile numerical analysis method, FEA can be applied to problems in solid mechanics, fluid mechanics, elasticity, and statics (Song *et al.* 2019; Jiang *et al.* 2021). These capabilities can be effectively extended to the mechanical analysis of wood processing. Research on FEA applications in wood processing primarily focuses on areas such as wood mechanical properties (Hu *et al.* 2019), wood drying (Tankut *et al.* 2014), and wood cutting processes (Nairn 2016).

In the study of wood mechanical properties, representative research topics often involve finite element modeling at the cellular scale to explore the micromechanical behavior of wood and determine mechanical parameters such as tensile and bending strengths. For wood drying processes, research focuses on finite element simulations of moisture transport during drying and on the mechanisms and predictive analysis of drying stress development. Due to the difficulty of analyzing the micromechanical properties and drying mechanisms of wood using conventional techniques, FEA provides distinct advantages by representing these microscopic characteristics and processes more intuitively through models. Furthermore, for the analysis of wood processing, FEA outperforms other methods. It is particularly advantageous for modeling and analysis in areas such as wood drying, cutting, and structural stress analysis, offering precise results at lower costs and under limited experimental conditions.

## THEORETICAL FOUNDATIONS OF THE APPLICATION OF FINITE ELEMENT METHODS IN WOOD PROCESSING

The theoretical foundation of the FEA method is an interdisciplinary integration that combines mechanical and numerical analysis techniques, providing a powerful tool for solving practical engineering problems. The mathematical basis of FEA includes principles such as the variational principle (Deng and Dargush 2021), differential equations, and function approximation (Bacuta and Bacuta 2023), which enable the transformation of higher-order differential equations into solvable algebraic equations. Given the complex and diverse biological structural characteristics of wood, these features significantly influence the simulation of wood processing using FEA. It is necessary to develop finite element models and algorithms tailored to wood, including specific element types and efficient solvers, to enhance simulation efficiency and accuracy. Such advancements rely on the application of FEA for material characterization, modeling of wood properties, and precise analysis of the mechanical forces involved during wood processing. This ensures reduced material wastage and improved utilization during production.

### Mathematical and Mechanical Foundations for FEA in Wood Processing

As a numerical technique, the core principle of FEA involves discretizing continuous physical problems into solvable algebraic systems. In wood processing simulations, the application of FEA is grounded in several fundamental mathematical principles, including the variational principle, differential equations, and function approximation. The variational principle, particularly the principle of minimum potential energy, forms the basis for structural optimization and equilibrium problems. This principle states that a system is in stable equilibrium when its potential energy is minimized; the method that flows from this principle can be employed to solve stress and displacement fields under equilibrium conditions (Wang 2010; Xuan *et al.* 2023).

Differential equations are used to describe physical phenomena such as heat conduction and fluid dynamics. Function approximation involves the use of shape functions to approximate physical quantities within a continuous domain, which are crucial in describing the local behavior of each element in finite element models (Carrera and Scano 2024). These shape functions play a pivotal role in FEA.

The FEA simulation process typically consists of three stages: preprocessing, solving, and postprocessing (Szabó *et al.* 2021). In the preprocessing stage, the model's geometry, material properties, boundary conditions, and loading conditions are defined. The solving stage involves assembling and solving algebraic equation systems derived from element stiffness matrices. The postprocessing stage includes analyzing and interpreting results, such as visualizing stress, strain, and displacement distributions.

In wood processing simulations, FEA discretizes the processing operation into finite elements, each defined by specific shape functions and material properties. The collective assembly of these elements forms the simulation model, enabling accurate representation of complex geometries and material characteristics in wood processing. Through appropriate mesh division and element selection, FEA captures localized deformations and stress distributions, facilitating predictions of mechanical behavior during processing. The anisotropic and heterogeneous nature of wood necessitates the inclusion of appropriate material models and boundary conditions in simulations (Zhang *et al.* 2014). For example, the mechanical behavior of wood requires constitutive models to describe its stress-strain relationships in different directions. Applications of FEA in wood processing also include predictions of cutting forces, temperature distribution, surface quality of workpieces, and analyses of tool-workpiece interactions.

## Finite Element Models and Algorithms Suitable for Wood Materials

FEA enables the examination of the complex mechanical behavior of wood. Developing finite element models suitable for wood requires accounting for its anisotropic and heterogeneous characteristics (Grytz *et al.* 2020). Anisotropic material models assign different material parameters, such as elastic modulus and Poisson's ratio, in different directions based on the mechanical properties of wood. Nonlinear elastic and plastic models can capture the nonlinear behavior of wood under stress, which is critical for simulating processes such as cutting (Li *et al.* 2022; Kuvik *et al.* 2024). Damage and fracture models are used to predict wood failure, particularly under severe loading conditions. Contact algorithms simulate the interactions between tools and wood, while thermo-mechanical coupling models analyze the effects of heat treatment on wood performance.

Simulations of wood processing require accurate experimental data for model validation and parameter calibration. For example, Zhou *et al.* (2020) developed a three-dimensional hygro-mechanical coupled model. This model reconstructs the microscopic pore structure of wood (average porosity 15%) using CT scanning and establishes governing equations based on an orthotropic elastic matrix (elastic moduli $E_L$ = 12.5 GPa, $E_R$ = 1.2 GPa) and effective diffusion coefficient ($D_{eff}$ = $2.5\times10^{-10}$ m²/s). Simulation results revealed that surface tensile stress peaks at 12 MPa during the initial drying phase, showing strong agreement (error <8%) with crack initiation locations monitored through acoustic emission experiments. By optimizing drying parameters (reducing heating rate to 2°C/h and decreasing humidity gradient by 20%), the final cracking rate was reduced to 8%. The results showed good agreement with experimental data, validating the effectiveness of the adopted finite element model (Zhou *et al.* 2020).

Vratuša proposed a material model for describing the nonlinear viscoelastic deformation of wood under stress. Through experimental testing and FEA, the study examined the mechanical responses of wood under various environmental conditions. The model simulated wood's heterogeneity and anisotropy and explored creep effects under prolonged loading. The results demonstrated the model's accuracy in predicting the stress-strain relationships and nonlinear deformation behavior of wood under complex loading conditions (Vratuša *et al.* 2017).

Felhő and Rakonczai (2019) explored the use of FEA to optimize parameters in wood processing to improve efficiency and product quality. The study focused on the effects of parameters such as cutting speed, feed rate, and cutting depth on the processing operation. By developing a three-dimensional finite element model of the cutting process, the study investigated how these parameters influence cutting forces, heat generation, and surface quality. Optimization results indicated that adjusting processing parameters significantly reduced energy consumption and improved product precision.

To achieve finer simulations of wood's microstructure and macroscopic performance, researchers have developed and refined Representative Volume Element

(RVE) models and multiscale models. These models provide in-depth insights into wood's internal structure and enable predictions of macroscopic mechanical behavior. Optimization algorithms offer references for determining processing parameters, helping identify cost-effective processing conditions (Li *et al.* 2022). Numerical solvers, the core of FEA software, handle large-scale algebraic equations to solve three-dimensional representations. Platforms such as ANSYS, ABAQUS, and COMSOL implement these solvers, enabling the resolution of complex problems in wood processing.

## FINITE ELEMENT APPLICATIONS IN WOOD PROCESSING

### Applications in Characterizing Wood Material Properties

*FEA of solid wood*

The mechanical behavior of solid wood is complex and variable. It is significantly influenced by factors such as shrinkage and swelling, knots, grain orientation, and internal defects. In finite element simulations, these characteristics must be accurately represented through appropriate material models and parameters to ensure the reliability and precision of the results. For instance, wood's nonlinear elastic and plastic behavior requires well-defined constitutive relations, while its anisotropy necessitates considering the effects of grain orientation in modeling.

In simulating growth stresses in wood, stress distribution and deformation at the cellular level are challenging to observe directly during external load application. To address this, Mishnaevsky and associates employed finite element methods to analyze crack shapes and stress concentration locations in wood cell walls, elucidating the deformation mechanisms at the cellular scale (Qing and Mishnaevsky 2010). On a macroscopic level, Ormarsson *et al.* (2009) used finite element modeling to study deformation caused by growth stresses during sawing. Their research revealed that radial growth stresses redistribute during the sawing process, leading to twisting deformation in sawn timber. The study highlighted that radial growth stress significantly influences the elastic modulus and microfibril angle strain along the wood's longitudinal direction.

Wood's anisotropic nature results in higher compressive and tensile strengths along the grain and comparatively lower strengths across the grain. Finite element software can intuitively simulate these mechanical characteristics, offering valuable guidance for wood processing techniques. For instance, Zhong *et al.* (2021) conducted finite element simulations on axial and transverse compression of wood, concluding that transverse compression exhibited linear and uniform deformation, whereas axial compression led to rapid collapse (Zhong *et al.* 2021).

A critical aspect of finite element simulation of solid wood's mechanical properties lies in capturing the continuous redistribution of stress during processing. Simulations should not be limited to instantaneous snapshots but must consider the continuous evolution of stress over time.

The macroscopic mechanical properties of wood are significantly influenced by its microstructure, such as the alternating arrangement of earlywood and latewood. Taking Norway spruce (*Picea abies*) as an example, the density difference between earlywood and latewood within its growth rings can reach 300 kg/m$^3$, resulting in radial bending strength fluctuations exceeding 40% (Kiraly *et al.* 2023). To analyze this phenomenon, Kiraly's team reconstructed the cellular structure of spruce cross-sections using high-resolution scanning (HSV spectral algorithm) and developed a hierarchical finite element model. In the model, earlywood was defined as low-density (450 kg/m$^3$), high-compliance regions (elastic modulus $E_R$ = 0.8 GPa), while latewood corresponded to high-density (750 kg/m³), high-specific-stiffness zones ($E_R$ = 1.5 GPa). Simulation results revealed that under three-point bending loads, stress concentration primarily occurred in latewood regions (peak stress 12 MPa), with earlywood absorbing energy through plastic deformation. The model-predicted failure modes coincided with experimental fracture locations (error <7%), providing cross-scale theoretical support for the mechanical design of solid wood components.

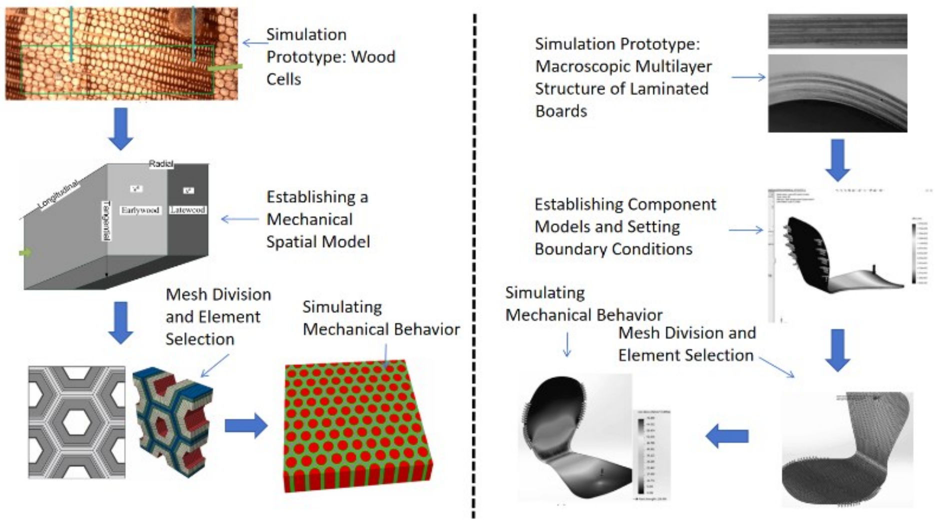


**Fig. 1.** Finite element simulation process of structures and stress in solid wood materials and engineered wood products

*FEA of engineered wood materials*

Engineered wood materials possess unique biomass properties compared to conventional homogeneous materials (Liu *et al.* 2019), necessitating the development of finite element models and algorithms tailored to these characteristics to enhance simulation efficiency and accuracy. These models often utilize specific element types, such as shell elements, beam elements, and solid elements, which can capture the behavior of wood materials across various scales. On the algorithmic front, wood-processing simulations frequently involve nonlinear problems, requiring iterative techniques such as the Newton-Raphson method (Wang and Zhang 2020) to solve nonlinear equations. For complex materials, efficient solvers are essential to handle large-scale systems while ensuring computational stability and convergence.

In the study of laminated wood bending behavior, Žiga *et al.* (2023) measured and calculated the deflection of three-layer laminated wood under free-end loading using both analytical and finite element methods. The results from both approaches exhibited high consistency, demonstrating that the stiffness and deflection characteristics of laminated wood are predominantly influenced by the fiber orientation of the outer layers (Žiga and Kačmarčik 2023). Regarding finger-jointed lumber, He Sheng *et al.* (2014) utilized finite element simulation to determine the end compression limits of *Pinus sylvestris* finger joints and modeled their bending elastic deformation process to obtain the modulus of elasticity. A comparison between simulation data and experimental results, after accounting for simulation errors, showed high consistency, confirming that FEA can reliably predict the mechanical properties of finger-jointed lumber.

For wood-plastic composites (WPCs), Charupeng and Kunthong (2022) employed a spatiotemporal finite element method using a time-discontinuous approach to solve for the time-dependent three-dimensional hygro-mechanical behavior of WPCs. This method provides an accurate, cost-effective means of simulating the shrinkage and swelling behavior of WPCs over time, advancing the understanding of diffusion dynamics.

The composition of engineered wood materials typically consists of numerous smaller elements. Analyzing the overall material properties requires first examining the individual characteristics of each element, including volume, type, morphology, and density, as well as the bonding performance between elements (Charuk *et al.* 2024). FEA, which discretizes the material into numerous small elements for simulation, aligns closely with the structural characteristics of engineered wood materials. Numerous studies have demonstrated that FEA can accurately predict the mechanical performance and failure behavior of engineered wood materials (Camú and Aicher 2018). By simulating factors such as the size, shape, density, and thickness of constituent elements, FEA facilitates the structural optimization of engineered wood products, enabling the design of higher-performance materials.

## FEA of the Wood Drying Process

The drying process is a critical step in the processing of wood materials. Due to the anisotropy of wood and variations in moisture content distribution, drying often induces drying stresses, which can lead to a series of defects such as warping, shrinkage, and cracking (Fu *et al.* 2021; Zhang *et al.* 2024). Consequently, understanding drying stresses and addressing related defects have long been focal points in the field of wood drying. FEA has been widely applied in this domain, enabling the development of moisture transport models and the prediction of drying stress distributions (Yin and Liu 2021). Through FEA-based modeling, drying stresses can be quantitatively analyzed with precision, efficiency, and minimal experimental error, facilitating the exploration of more accurate drying mechanisms.

### *FEA of drying stresses*

In the study of drying stresses, Redman *et al.* (2018) applied FEA to analyze the drying stresses in lemon-scented gum (*Corymbia citriodora*) and shining gum (*Eucalyptus nitens*) during conventional and vacuum drying processes. Their analysis predicted the magnitude and distribution of end-cracking stresses and surface defects in these species, revealing that *Eucalyptus citriodora* was more prone to end cracking. Pérez-Peña *et al.* (2018) investigated drying stresses in eucalyptus wood caused by moisture content changes, employing FEA to establish a moisture transport model incorporating the concept of an effective diffusion coefficient. Using a mathematical model based on second-order nonlinear partial differential equations, they simulated the stress-strain and moisture diffusion processes during drying. Experimental validation demonstrated that FEA effectively modeled the deformation, drying stresses, and moisture gradients, achieving satisfactory results.

With advancements in computational technology, FEA-based theoretical modeling for predicting drying stresses has become increasingly refined. Research on macroscopic-scale drying stress modeling has emerged as a prominent focus. However, since the root cause of drying stresses lies in the microscopic structure of wood (Saleh 2021; Yang and Berglund 2021), current FEA studies have largely concentrated on developing constitutive models of wood without integrating heat and mass transfer processes during drying. This limits the comprehensive understanding of drying mechanisms. Future research is expected to focus on establishing drying stress models at micro- and ultra-microscopic scales while improving their practical applicability and adaptability to real-world scenarios.

*FEA of mass transfer during drying*

During the drying process, moisture in wood dissipates in various forms. However, the rate of moisture loss is not constant, and the distribution of moisture is uneven, leading to drying defects such as warping and cracking. FEA provides a robust tool to investigate the mechanisms of moisture transfer and optimize drying processes (Liu *et al.* 2022, 2023, 2024, 2025; Yang and Liu 2022). For instance, Ferguson (1995) applied FEA to develop a numerical model of moisture migration in spruce during drying, incorporating deformation and twisting effects. Unlike conventional numerical methods, the control-volume finite element method employed in this study was independent of structured fixed grids, enabling accurate simulations using unstructured grids.

Zeng *et al.* (2024) combined near-infrared spectral imaging and X-ray computed tomography with FEA to construct a 3D model of moisture transfer in wood. This approach visualized the hygroscopic and desorption processes within the wood and used the results to adjust FEA parameters. Their model serves as a foundation for optimizing drying parameters and improving drying quality (Zeng *et al.* 2024). Similarly, Suchomelová *et al.* (2019) performed FEA-based numerical simulations of coupled heat and mass transfer during kiln drying, focusing on moisture movement below the fiber saturation point. Four numerical models were developed, with one employing linear simulation for average moisture content predictions and the other three using nonlinear simulations with temperature and moisture content as variables. Results demonstrated that nonlinear models more accurately calculated moisture content distribution, showing strong alignment with standard requirements (Suchomelová *et al.* 2019).

Florisson *et al.* (2020) introduced an FEA tool to simulate transient nonlinear moisture transport in wood, aiming to enhance the accuracy of bending behavior simulations under changing climatic conditions. Calibrating the model with Norway spruce samples, the study emphasized the critical role of sorption hysteresis in predicting moisture distribution. Combining nonlinear properties and hysteresis effects yielded accurate predictions of moisture gradients and transfer processes.

The construction of moisture migration models for wood drying provides an intuitive explanation for the origins of drying stresses and offers theoretical support for reducing drying defects. Existing research suggests that FEA of moisture migration can substantially contribute to enhancing drying quality by providing a numerical basis for optimization. However, most studies focus on macroscopic-scale simulations of moisture transfer during drying, with limited exploration of microscale mechanisms such as capillary phenomena. Addressing these challenges remains a key research priority.

*FEA of heat transfer during drying*

To study heat and mass transfer during drying, Zhao and Cai (2017) developed a comprehensive 3D mathematical model to simulate convective heat and mass transfer in conventionally stacked wood within a drying chamber. This model accounted for internal heat and mass transfer in the wood as well as the influence of environmental fluid flow. Numerical solutions were obtained using COMSOL Multiphysics and validated with experimental data. Results indicated that airflow nonuniformity was a primary cause of temperature and moisture content disparities within the wood, with these differences diminishing as drying progressed. Additionally, transient humidity accumulation associated with airflow and evaporation rates was observed in the drying chamber.

Kuznetsov *et al.* (2021) investigated heat transfer during the dehydration of wet biomass layers in a high-temperature gas environment. They identified fundamental principles of temperature field formation during the dehydration process. Results revealed the formation of a heterogeneous temperature field, resulting from complex interactions of heat conduction, phase transitions (evaporation and condensation), and vapor diffusion through the porous biomass framework. Localized temperature reductions were attributed to intense heat absorption during evaporation and vapor filtration.

Current studies on heat transfer simulation during drying face limitations, such as insufficient representation of wood's anisotropic and porous microstructures and incomplete modeling of multiphysics interactions during heat transfer (Trcala 2012; Chávez *et al.* 2021). To address these issues, FEA models must enhance their depiction of wood's microstructural complexity, capturing its anisotropy and heterogeneity to improve physical realism. Precise boundary conditions, consistent with actual drying environments, are critical for simulation accuracy. Future research should deepen the analysis of coupled heat and mass transfer effects to understand their interactions during the drying process.

## FEA of Cutting Processes for Wood Materials

The cutting process of wood materials is prone to various surface defects, including deformation, burrs, grain swelling, and wave-like knife marks, depending on the cutting parameters employed (Badruddin *et al.* 2017; Garoz *et al.* 2019; Qing *et al.* 2021). In addition, improper design of cutting parameters can lead to wear and damage to cutting tools and equipment. Therefore, analyzing the cutting process from the perspective of cutting mechanisms is essential for optimizing cutting parameters and designing cutting tools. Given the rapid speed of wood cutting, conventional observation methods cannot effectively record the process, and simple formulas are inadequate for accurately analyzing cutting behavior (Sharma *et al.* 2022). As a highly efficient numerical simulation approach, FEA can be applied in the study of cutting processes and the design and analysis of cutting equipment, particularly in the era of advanced computer simulation technologies.

### *FEA of the cutting process*

FEA in the context of wood material cutting typically focuses on chip formation mechanisms, stress-strain simulations of wooden components, and wood splitting behavior (Ding *et al.* 2023). Fu and Jia (2013) employed FEA to simulate the chip formation mechanism, cutting forces, and stress-strain behavior in laminated veneer lumber (LVL) during cutting. Their analysis revealed that longitudinal type-II chip formation occurs due to the material near the cutting tool being prematurely crushed under high pressure. As the cutting progresses, the chip deformation zone develops compressive, shear, bending, or tensile stresses, with bending stress being the predominant factor, resulting in curved chip morphology.

Bôas *et al.* (2023) conducted FEA on the cutting behavior of saw blades in log processing. Since the primary stress during sawing is shear stress, the FEA model focused on the mechanical behavior of the saw blade edges. The model applied tensile stress to the blade to simulate deformation and perpendicular loads on the saw teeth to capture the forces experienced during sawing. Zhao *et al.* (2019) performed FEA to investigate the fracture behavior of wood fibers in spruce during cutting and predicted machining quality under various cutting conditions. The study involved constructing a 3D model of spruce fibers and analyzing their crushing and tensile fracture behavior at the microscopic level during cutting. Simulation results provided an energy consumption formula for the cutting process, which was validated with experimental data, achieving an accuracy exceeding 90%. This model offers guidance for optimizing cutting parameters and contributes to the establishment of cutting quality standards.

Although numerous factors influence the cutting process and its outcomes, traditional experimental methods are limited in their ability to analyze the entire cutting process. These methods often require sequential analysis of individual factors before integrating results, which imposes constraints on time and cost. FEA, in contrast, enables the integration of transient simulations to achieve continuous cutting process modeling over a spatiotemporal domain. Additionally, specific moments within the cutting process can be analyzed for phenomena such as cutting heat, thermal stress, tool fatigue, and wear rates. This capability allows for intuitive and systematic insights into critical aspects of the cutting process, thereby improving cutting parameters and standards and enhancing overall cutting quality. However, current FEA studies have not fully addressed the microscopic fiber fracture and crushing behaviors of wood materials during cutting. Future research in this area is expected to focus on the simulation of material behaviors at the microphysical scale.

*FEA of cutting equipment*

The design of cutting equipment, including structural components and tools, requires consideration of factors such as equipment stability, processing efficiency, static mechanical models (Toson *et al.* 2014), cutting speed, and cutting angle (Khelifa *et al.* 2015). FEA offers advantages of low cost, high efficiency, and precision in the auxiliary design of cutting equipment (Chen *et al.* 2020). Optimal wood-cutting tool design necessitates addressing the degradation of cutting edges due to lignocellulosic fiber abrasion. For instance, when longitudinally cutting Scots pine (*Pinus sylvestris*), saw teeth frequently chip due to root stress concentration ($K_t = 3.2$), resulting in a tool lifespan of only 40 hours (Warguła *et al.* 2023). To analyze the failure mechanism, Bôas *et al.* (2023) developed a 3D dynamic explicit model of saw blade-wood interaction, defining wood's transverse tensile strength (4 MPa) and fiber damage threshold (failure at strain >5%). The Johnson-Cook plasticity model ($A$=1200 MPa, $n$=0.2) was employed to characterize the saw blade's mechanical behavior. Simulations revealed that increasing the tooth root fillet radius (0.5 mm→1.2 mm) reduces stress peaks by 40%, extending tool life to 65 hours (experimental error <10%). This research demonstrates the critical role of FEA in tool design and resource-efficient operations.

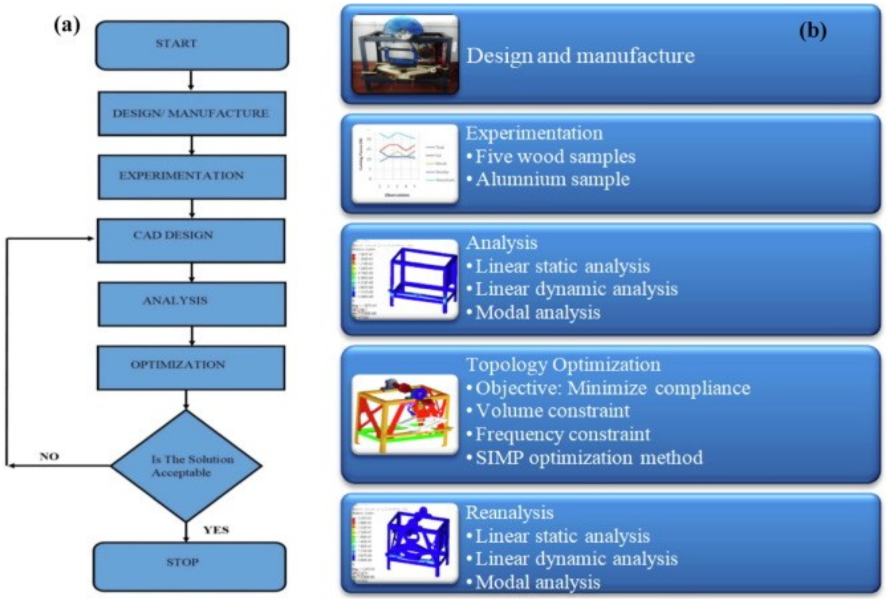


**Fig. 2.** Typical Finite Element Mechanical Simulation Process for Wood Cutting Machinery (a) Methodology followed in the present work, and (b) Pictorial view

Li *et al.* (2015) employed ABAQUS to analyze the effects of a novel multi-point, multi-position tensioning process on circular saw blade performance. By optimizing parameters such as loading force, radial distance, circumference, and outermost radius, the study demonstrated significant improvements in the natural frequency and tangential tensile stress at the blade edges, enhancing stability and extending the lifespan of the blades. The findings verified the accuracy of the simulation model and enabled the proposal of two parameter optimization strategies, addressing issues such as thermal stress and deformation in traditional tensioning processes. This research provides theoretical and practical guidance for improving wood processing efficiency.

In summary, FEA has been widely applied in the static and dynamic analysis of cutting equipment and the design and manufacture of cutting tools. It shows promising potential for optimizing equipment structure, cutting tools, and parameters, as well as machining processes. However, cutting equipment often operates under high-intensity conditions, leading to fatigue and wear in components and tools, which alters their structural performance over time and reduces productivity. Current studies largely focus on short-term simulations of equipment under specific working conditions, making it difficult to analyze equipment behavior over extended periods. Addressing this limitation represents a critical challenge and research focus in the field of FEA for cutting processes.

## Application of Finite Element Technology in Wood Processing Optimization and Design

The application of FEA in wood processing has significantly advanced the design optimization practices in this field. This method plays a critical role in various key stages, including stress optimization, structural design, and processing equipment design. In terms of stress optimization, FEA can simulate the stress distribution in wood during processing, predict areas of stress concentration, and adjust process parameters to reduce the risks of cracking and deformation (De Luca 2017). Structural design optimization uses FEA to assess the response under loading conditions, streamlining the design process while ensuring the stability and safety of the structure. These optimization measures improve the efficiency and product quality of wood processing and contribute to the sustainable utilization of resources. In the future, the application of FEA in this field is expected to expand further.

*Stress optimization in wood processing*

Stress optimization during wood processing is a crucial step in ensuring that products have sufficient strength and stability during both manufacturing and usage. Through FEA, it is possible to simulate the stress distribution in wood under different processing conditions, predict potential stress concentration areas, and guide adjustments to process parameters (Li and Zhang 2019).

The deformation and stress concentration of glued laminated timber under hot and humid environments are key challenges limiting its engineering applications. Ormarsson and Dahlblom (2013) developed a hygro-viscoelastic coupling model for Norway spruce glulam beams, simulating the moisture absorption process from fiber saturation point (FSP=30%) to equilibrium moisture content (EMC=12%). The model incorporated anisotropic hygroscopic expansion coefficients (radial $\beta_R$=0.25%/%MC, tangential $\beta_T$=0.35%/%MC) and time-dependent viscoelastic parameters (relaxation modulus $E(t)=E_0e^{(-t/\tau)}$ with $\tau$=120 hours), thereby successfully predicting moisture gradients and stress distributions within beam cross-sections. Simulations revealed a 15% moisture differential between surface and core layers under 80% relative humidity, generating maximum tensile stresses of 6 MPa. Through optimized adhesive layer thickness (0.3 mm → 0.5 mm) and cross-alternated orthogonal lamination arrangements, peak stresses were reduced to 3.5 MPa with measured deformation decreasing by 42%. The results showed that the stress distribution within the cross-section of the beam is influenced by environmental humidity, which in turn affects the moisture content of the beam. Under humid conditions, a significant moisture gradient develops within the beam's cross-section, providing guidance for avoiding deformation due to stress during processing.

Chiniforush *et al.* (2022) conducted an extensive experimental-numerical study on the stress-strain behavior of spruce cross-laminated timber (CLT). They measured the swelling coefficient, shrinkage coefficient, and thermal expansion coefficient of spruce CLT under specific temperature conditions and developed a three-dimensional nonlinear FEA model. The model considered the impact of the adhesive layer on the performance of laminated panels. The results indicated that when the moisture content of the wood is below the fiber saturation point, the FEA model aligns well with experimental data for simulating the moisture-induced stress in glued timber (Chiniforush *et al.* 2022).

Podibka (2021) used FEA to establish a model for the physical and mechanical properties of beech (*Fagus sylvatica* L.) veneers used in furniture production, developing a method to calculate the overall stress-strain behavior of beech wood. This method combines environmental temperature and humidity changes with the wood's intrinsic physical-mechanical properties and anisotropy to account for the wood's shrinkage and swelling behavior. Using this system, the deformation and other defects of beech wood veneers can be predicted and corrected, ensuring dimensional stability during processing and providing a theoretical foundation for solid wood furniture production.

Navaranjan (2002) developed a cellular-level FEA model to define the microscopic structural properties of cork cells, using mathematical functions to describe the wood's density, microfibril angle, and moisture content. This model explored the dimensional changes of cork related to moisture content. Along with model development, experimental measurements of cork fiber cell shrinkage and expansion coefficients were conducted, with the results showing a good fit between the FEA model and experimental data.

Stress optimization is key to ensuring the quality of wood product processing. Due to the varying properties of different wood species, FEA-based stress-strain analysis models must be adjusted according to the specific characteristics of each wood type to determine appropriate stress optimization methods.

*Optimization of wood structural design*

Wood structural design optimization aims to enhance the load-bearing capacity and stability of structures while minimizing material usage. Using FEA, designers can predict the load response of a structure during the design phase and evaluate the performance of different design options. Through iterative analysis, the optimal structural layout and connection methods can be chosen, ensuring efficient material distribution while guaranteeing structural reliability (Stanić *et al.* 2016).

To address the need for balancing lightweight design and load-bearing capacity in wooden frames of upholstered furniture, Matwiej *et al*. (2022) conducted a study on a *Pinus sylvestris* frame by developing a three-dimensional discrete finite element model to simulate its stress-strain response under a standard 300 N load. The model incorporated the orthotropic anisotropy of wood (longitudinal elastic modulus $E_L$=10 GPa, radial elastic modulus $E_R$=1.2 GPa) and the nonlinear contact behavior at joints (friction coefficient $\mu$=0.2). Initial analysis revealed that the equivalent strain at frame joints reached 1.8%, which exceeded the safety threshold of 1.5%. Guided by finite element analysis, structural optimizations were implemented: 20×20 mm pine reinforcements were added to critical joints, reducing strain to 1.2%, while the main beam thickness was reduced from 40 mm to 30 mm, and low-stress material regions were removed *via* topology optimization, achieving a 15% weight reduction. The optimized frame maintained structural stiffness (deflection < 2 mm) while lowering material costs by 12%. The results showed that adding wooden strips at the frame joints significantly improved the deformation and strength of the upholstered furniture frame. Whether using solid wood or laminated wood, appropriately sized finger-jointed laminated panels did not result in a loss of stiffness, but, in some cases, enhanced stiffness, reducing displacement under standard loads. The study also suggested that using larger cross-sectional elements, shorter components, and meeting material quality requirements would not significantly affect the strength of the tested components, providing new insights and scientific evidence for the design of upholstered furniture frames.

Ceylan *et al.* (2021) conducted structural analysis of wooden chairs made from Scots pine and Oriental beech using FEA. The research team built and tested 30 full-scale chairs assembled with polyvinyl acetate glue and tested them in three main loading directions: front, rear, and backrest. The experimental results indicated that beech chairs met medium load-bearing standards in both the front and rear directions and high load-bearing standards in the backrest direction, while Scots pine chairs met light to medium load-bearing standards in all tested directions. FEA analysis provided reasonable estimates of the chairs' strength and failure behavior, validating the effectiveness of combining structural analysis with performance testing in furniture design and offering quantitative information for chair design. This approach is applicable to the design of other types of furniture and helps improve reliability and durability, providing a systematic methodology for furniture engineering design.

FEA plays a critical role in optimizing wood structural design by providing a detailed understanding of the load-bearing mechanisms within wood structures, offering scientific evidence to improve structural performance. By using FEA simulations, designers can predict the internal stress distribution within wood structures during the design phase and optimize the structural layout to improve stability and durability. This approach not only reduces structural defects but also enhances design flexibility and innovation, providing designers with a reliable numerical simulation basis that leads to more precise design decisions.

While FEA-based studies on wood structural stress have become comprehensive, research on hybrid structures combining wood with other materials, such as wood-metal or wood-organic material composites, remains underdeveloped. Additionally, after wood modification or deep processing, the mechanical strength in different directions may change compared to unmodified wood, which could impact the overall load-bearing capacity and stability of the wood structure. Therefore, future research in the field of FEA for wood structure design optimization should integrate new wood-based composite materials and wood modification technologies.

## CONCLUSIONS AND PROSPECTS

The application of FEA in wood processing has demonstrated transformative potential, yet critical challenges persist with respect to scalability, technological integration, and industrial validation. For instance, multiscale drying simulations demand prohibitive computational resources, limiting their practical adoption. To overcome these barriers, prioritized efforts should focus on GPU-accelerated adaptive meshing and AI-embedded solvers, as exemplified by a 70% efficiency gain in metal-forming simulations. Concurrently, integrating FEA with IoT-enabled digital twins could enable real-time adaptive control in industrial kilns, while sustainability metrics (*e.g.*, carbon footprint) must be woven into optimization workflows. Future research must bridge the gap between academic models and factory-floor complexity, ensuring FEA evolves from a predictive tool to a cornerstone of sustainable, intelligent wood processing. The following aspects can serve as a reference for the development trajectory of FEA technology as it continues to evolve:

### Optimization of Finite Element Model Databases for Wood Materials and Products, and Improvement of FEA Methods

Currently, the finite element models in the field of wood processing are often based on mesh partitioning, boundary division, and node connection parameters that are either fine-tuned from models of other materials or adjusted using idealized assumptions. Due to the uncertain characteristics of wood as a biomass material, future research will focus on developing more accurate finite element models to improve the precision of simulation results. This will include more refined simulations of the cellular structure of wood and predictions of wood behavior under varying environmental conditions.

Additionally, existing FEA models struggle to balance computational efficiency with the resolution required for multiscale simulations. For instance, simulating wood drying at both cellular (μm-scale) and structural (m-scale) levels demands terabytes of memory and weeks of computation, even on high-performance clusters. To address this, future research should prioritize adaptive mesh refinement and GPU-accelerated solvers, as demonstrated in metal-forming simulations where computation time was significantly reduced.

Therefore, it is crucial to optimize the finite element models for wood materials and products, analyzing how the specific properties of wood affect the final product, ensuring the accuracy and consistency of the FEA results within the domain of wood materials.

### Emphasis on the Application of Finite Element Models in New Wood Processing Technologies

In recent years, a range of new wood processing technologies has emerged, such as computer-controlled systems, AI deep learning, and digital production methods. The integration of FEM and these technologies will further automate and intelligentize the wood processing industry, improving production efficiency and product quality.

For example, the future development trend of FEM could involve integration with AI and the Internet of Things (IoT): While AI-driven parameter optimization (*e.g.*, neural networks for constitutive model calibration) shows promise, most FEM software lacks native interfaces for AI frameworks, forcing researchers to rely on manual data pipelines. Developing embedded AI modules (*e.g*., TensorFlow-integrated solvers) and real-time IoT connectivity (*e.g*., sensor-fed humidity updates during drying) could enable adaptive simulations that respond to dynamic processing conditions.

Given the global shortage of forest resources, transitioning FEA technology toward digitalization and AI will not only align with contemporary technological trends and drive product innovation but will also conserve wood resources, making wood processing more sustainable and environmentally friendly.

### Development of FEA from Single-Factor to Multi-Factor Coupled Analysis

During the wood processing stage, the interaction of multiple physical fields (such as mechanics, thermodynamics, and moisture) plays a critical role in determining the processing results. The evolution of FEA from single-factor to multi-factor coupled frameworks has become imperative in wood processing research, driven by the intrinsic interdependencies between mechanical, thermal, and hygroscopic phenomena. For instance, when analyzing the cutting process of laminated veneer lumber (LVL), not only the inherent properties of the veneer itself need to be considered, but also the impact of adhesive layers on the mechanical behavior of the individual layers, as well as the cutting forces acting on the blades during the process. Therefore, future advancements should prioritize three synergistic approaches:

(1) Hierarchical Modeling: Developing multi-scale frameworks that link microscopic cellular behavior to macroscopic process outcomes, as demonstrated in recent studies on wood drying.

(2) Standardized Material Databases: Establishing open-access repositories for wood-specific parameters (*e.g*., moisture-dependent elastic moduli, adhesive creep coefficients) to reduce calibration uncertainty.

(3) Hybrid Numerical Methods: Combining FEA with discrete element methods (DEM) to better capture discontinuous phenomena like fiber fracture during cutting.

By addressing these priorities through coordinated computational and experimental efforts, coupled FEA can transform into a predictive tool capable of unraveling cross-physical synergies in wood processing. This may be a critical pathway toward defect-minimized manufacturing and sustainable resource utilization through scientifically informed process optimization.

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