Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.3, July 2026, pp. 02603016-01 ~ 02603016-014
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i3.3440

Integrated Sustainable Manufacturing and Waste Management Framework for Medium-Density Fiberboard (MDF): Finite Element Methods-Based Structural Optimization for Bookshelf Applications

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Abstract. Medium-density fiberboard (MDF) is commonly used in furniture manufacture because of its consistent qualities, low cost, and ease of processing. However, its relatively short lifespan and rising market demand have resulted in substantial waste generation, posing serious environmental and disposal concerns. This study provides an integrated sustainable manufacturing and waste management framework for MDF that incorporates artificial intelligence technology and finite element method (FEM)-based structural optimization for bookshelf applications. The structural performance is evaluated by numerical simulations focusing on von mises stress, displacement, and safety factor. These findings indicate that combining FEM-based design optimization with intelligent waste management strategies might enhance the structural performance and sustainability of MDF products. This study emphasizes the necessity of merging advanced simulation, artificial intelligence, and life-cycle assessment methodologies to create intelligent, efficient, and ecologically responsible wood-based manufacturing systems.

Keywords: MDF, waste management, wood industry, manufacturing strategy, bookshelf

(Received 2026-02-01, Revised 2026-04-19, Accepted 2026-04-27, Available Online by 2026-06-01)

1. Introduction

One of the few natural resources that can be replenished is wood. Wood-frame homes and furniture, newspapers, books, and magazines, railroad ties and bridges, utility polishing and fence posts, fuelwood, textiles, and organic compounds are all examples of how it permeates the economy and our daily lives. Additionally, wood and wood-derived goods retain carbon, which helps to reduce atmospheric carbon dioxide. Wood is generally defined as the hardened part of a plant, especially the trunk and branches, which are rich in lignin. Wood has many uses, including (a) building materials: wood is used as the main material in the construction of houses, bridges, and various other structures, (b) furniture: wood is used to make various types of furniture, such as tables, chairs, cupboards, and others, (c) fuel: wood is also used as fuel, both for cooking and heating, and (d) paper material: wood is the main raw material in making paper [1-2].

In various industries, from construction to furniture production, wood manufacturing is an essential process. When it comes to education, knowing how to make wood gives students technical skills, problem-solving skills, and knowledge about using sustainable materials. It also prepares students for careers in carpentry, woodworking, and industrial design**.** The wood industry is key for sustainability and an important economic activity in many countries. In manufacturing plants, wood variability turns operation management more complex[3]. As an industrial method of enhancing some wood qualities, wood heat treatment has grown dramatically in the last several years and continues to do so. Equilibrium moisture, dimensional stability, durability, and mechanical characteristics were the primary subjects of the initial heat treatment investigations. While current research concentrates on quality control, modeling, and investigate the causes of the improvements, mass loss, wettability, wood color, and chemical transformation have all been thoroughly explored since then [4]. In building and construction engineering education, one of the materials given is about wood.

In the industrial wood manufacturing sector, efficiency, product quality, and environmental sustainability are critical factors influencing competitiveness and profitability. However, many manufacturing operations continue to face significant challenges related to inconsistent wood quality, inefficient utilization of raw materials, and inadequate waste management practices. These issues not only affect production outcomes but also contribute to increased costs and environmental degradation. One of the root causes lies in the limited integration of comprehensive wood quality analysis in the manufacturing process. Variations in wood species, moisture content, grain structure, and mechanical properties are often overlooked or poorly managed, leading to defects, reduced durability, and material wastage. In parallel, industrial wood waste—comprising off-cuts, sawdust, and defective products—is frequently underutilized, despite its potential for recycling, energy production, or value-added applications.

This situation underscores a critical need for systematic approaches that allow industries to better understand and analyze the properties of wood during processing while simultaneously implementing sustainable waste management strategies. Addressing these issues is essential for improving operational efficiency, product consistency, and environmental performance in the wood manufacturing industry. When making furniture, medium-density fiberboard (MDF) is frequently utilized. The volume of garbage generated has increased due to the short relative lifetime and the growth in demand, raising disposal concerns. Although the majority of this material comes from renewable sources, very little of it is recycled. The MDF global market is expected to increase from USD 39.04 billion in 2021 to USD 57.11 billion in 2028, from its 2020 value of USD 38.25 billion. China is the market leader in the Asia-Pacific area, controlling 90% of the regional market [5].

Bookshelves are one of the many uses for MDF in interior construction because of its uniformity, ease of shaping, and smooth surface that allows for a variety of finishing techniques. MDF also provides better dimensional stability and lower production costs than solid wood, making it a popular option in the contemporary furniture industry. However, there are still issues with MDF's mechanical strength when it comes to bookshelves, especially when it comes to withstanding bending pressures brought on by the buildup of books over time. Finite Element Methods (FEM) are a useful tool for designing MDF bookshelves with the best possible mechanical performance. A strong and adaptable technique for creating Medium-Density Fiberboard (MDF) bookshelves with the best mechanical performance while upholding sustainable production standards is Finite Element Methods (FEM).

FEM enables engineers to optimize material utilization, decrease waste throughout the production process, and reduce overdesign by precisely simulating stress distribution, deformation, and structural integrity under a range of loading circumstances. This lessens the impact on the environment, uses resources more effectively, and uses less energy. In order to ensure that the finished product not only satisfies strength and durability requirements but also conforms to environmental sustainability goals and circular economy practices. This study aims to develop an integrated framework combining FEM-based structural optimization and sustainable MDF manufacturing.

Research Questions:

a. How does the integrated wood manufacturing and MDF waste processing process work using artificial intelligence?

b. How does the MDF structure perform in bookshelf applications?

2. Methods

This study employed a mixed-methods approach. A qualitative approach was used to explain sustainable wood manufacturing integrated with an artificial intelligence model. A simulation approach using finite element methods was used to test the performance of a bookshelf design as an application of MDF wood processing. The materials used in the simulation of von mises stress, displacement, and safety factor use MDF. Material specifications are shown in Table 1. The bookshelf design is shown in Figure 1.

Table 1. Materials

Materials	Density (g/cm^3)	Young's Modulus (GPa)	Yield strength (MPa)	Ultimate Tensile strength (MPa)
MDF	0.62	2.779	32.11	32.11

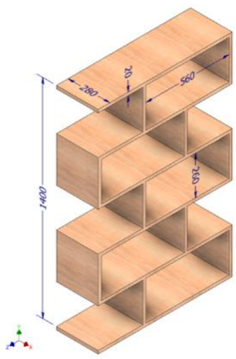


Figure 1. Dimensions of bookcases used in the study (mm)

3. Results and Discussion

3.1. Wood Manufacturing Process

Wood is a truly sustainable and aesthetically pleasant material used in indoor and outdoor applications. Every material, including wood, is expected to have long-term durability and to retain its original appearance over time. Wood manufacturing is the process of processing wood, either raw or semi-finished, into finished products ready for use, such as furniture, construction materials, or other wood products. The importance of using a manufacturing system for the wood industry is to increase production efficiency, ensure product consistency, optimize product quality, and increase production capacity. Figure 2 shows the wood manufacturing process.

Figure 2. Wood manufacturing process

The wood manufacturing process involves several key stages, each requiring precision and expertise. The main steps include[6]:

a) Raw Material Selection[7-9]: Choosing the appropriate type of wood based on its properties, such as hardness, grain pattern, resistance, and durability. Wood has several characteristics that need to be considered in the selection process. The following are some of the Fire Resistance properties of wood. Apart from Ignition Times of Wood Species, other parameters for determining raw wood material include specific gravity, wood color, adhesive strength, and formaldehyde emissions [10]. Three pillars of wood material sustainability include raw material procurement, material manufacturing, and end of life time [11].

In making building structures from wood, several factors that need to be considered include the load duration factor, wet service factor, temperature factor, beam stability factor, shape factor, surface usage factor, notch factor, repetition factor, column stability factor, bending stiffness factor, bearing area factor, format conversion factor, resistance factor, time factor, and modulus of elasticity [12]. Predicting wood species is one of the ways artificial intelligence is being developed. Many industries, like the building and furniture production sectors, require the ability to identify different types of wood [13]. In selecting materials for MDF, Graphite Phenolic Spheres (GPS) are used as a coating material or fire-retardant additive that can increase the thermal resistance and ignition time of MDF[14].

b) Log Processing[15-16]: Logs are debarked, cut, and processed into usable lumber through sawing and milling. The material, the method, and the transformation technology are influencing aspects for wood manufacturing processes. A number of variables are integrated in cutting processes, with the cutting tool playing a significant role. These have an effect on landings, materials, motors, auxiliary systems, assets, spinning mechanisms, and other equipment. In longitudinal sawing, working angles α, β and γ of the cutting tool, geometry, feed per tooth, the feed and cutting speed movement must be optimized[3]. Figure 3 shows a typical sawmill tool and material interaction. Basic parameters of circular saws are shown in Table 2.

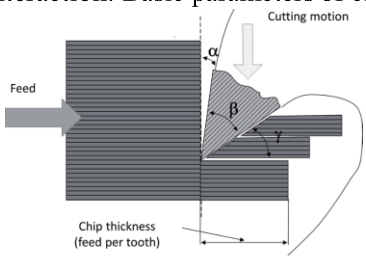


Figure 3. A typical sawmill tool and material interaction

Table 2. Basic Parameters of Circular Saws [17]

Basic Dimensions	Saw diameter D (mm)	Saw width B (mm)	Cutting clearance angle *a* (°)	Cutting-edge side rake (°)	No. of teeth
Circular saw made of high-speed steel	600	5.4	20	-5, 0, 5, 10	56
Circular saw with cemented carbide plate	600	5.4	15	-10,0 10, 20	54

Defining the value of individual parts of force F is quite difficult and depends on many aspects. The part of force F in the direction of cutting feed F is called cutting force and it is used for practical calculations of energetic relations during the cutting process. The part perpendicular to force F represents the pressure of the circular saw tooth on the surface of a machined surface and it is called withdrawal force Fc. Cutting force Fc is shown in equation (1). Cutting force Fc acting on the tooth of a circular saw takes chips at the width b and thickness h. The cutting force value is then given by the multiplication of cutting resistance for disintegrated material K and the surface of chip crosscutting[17].

$$\mathrm{Fc} = \mathrm{K} \times \mathrm{b} \times \mathrm{h} \qquad (1)$$

The dimension of cutting work Ac is shown in equation (2). The dimension of cutting work Ac on condition that the cutting resistance is constant in all phases of the cutting process can be defined as follows, where, l is cutting way of a tooth in the material (mm). The cutting power is shown in equation (3). The cutting power is defined as the multiplication of cutting force Fc and cutting speed v_c. We can calculate the cutting power also by means of the torque, where: Mk is torque (N·m), D is diameter of a circular saw (m), can be defined as follows equation (4).

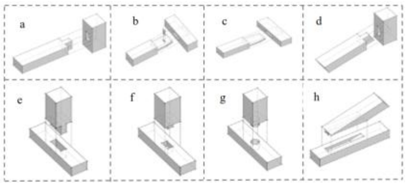
$$Ac = Fc \times l = K \times b \times h \times l \qquad (2)$$
$$Pc = Fc\ x\ v_c \ \ (\mathrm{W}) \qquad (3)$$
$$\mathrm{Pc} = \frac{2\ x\ M_k\ x\ V_c}{D} \qquad (4)$$

The intensive use of wood in furniture, building, bridges, and of aluminum in transportation and construction, underscores the economic importance of these building materials. To improve the efficiency of production and manufacturing processes, saw cutting machines are needed. Programmable Logic Controller and Human Machine Interface (HMI) are used for production efficiency[18-20]. For cutting machine based on programmable logic controller based machine has acquired faster execution time and is more efficient in functioning along with safety measures to reject bad material and ease in operation[21]. A key component of making cutting operations more convenient, speedy, and user-friendly for users is the design of HMI interactive screens.

c) Drying [22]: Wood is dried to reduce moisture content, prevent warping and ensure structural stability. Wood drying is categorized as a separation operation. Water must be eliminated from a multiphase system with a complex solid structure in order to achieve the required solid phase and water content mix. Thus, by considering the drying process as a collection of simultaneous heat, mass, and momentum transfer processes involving the phase shift of water within the complex material that is wood, it is possible to understand it. The process of drying entails the simultaneous movement of mass (water and water vapor), heat, and momentum. It is explained by basic equations, which are simultaneous differential equations that represent the fluxes of heat and water [22]. To guarantee that the wood maintains its stability and physical integrity during use and remanufacturing, drying is a crucial step in the wood processing process. Uneven moisture content between and within boards, board distortion, residual drying forces that may cause internal and external checking, and wood collapse are only a few of the drying flaws that may arise during industrial drying[18].
d) Cutting and Shaping[23-24]: Processed wood is cut into specific shapes and sizes using saws, Computer Numerical Control (CNC) machines, and other woodworking tools. The processing of wood-based panels such as plywood, particleboard and fiberboard, which are widely used in the industry. With CNC milling machines has been increasing recently[18]. The wood treatment process and the selection of CNC machine rpm will affect the surface of the wood. The surface roughness increases with increasing feed rate, but decreases with increasing spindle speed in

wood treated with compression (densification 20-40%) [25]. The densification techniques are referred to by different terms in the literature. Densification is the most widely used term. As soon as densified wood is exposed to moisture, it usually recovers from compression and returns to almost its initial condition after being soaked in water [26].

e) Joining and Assembly[27-28]: Components are joined together using adhesives, nails, screws, or advanced joining techniques. Wood joints are a technique for joining two or more pieces of wood together to form a single structure. Wood joints are used to meet specific length, width, or height requirements. Wood joints are important for the structural strength of a building, as well as the aesthetics of the building. Wood joints allow for the creation of complex and aesthetically pleasing building shapes and designs. Patterns of the expansion of the teak joint include joints in wooden planks that are not fully connected, rectangular wooden joints, square wooden joints, the triangular wooden joint, cylindrical wooden joint is with a hole for the joint, hexagonal joint inserts with joint pin slots[29]. Variations of mortise-and-tenon joints are shown in Figure 4.



(a) Blind mortise and tenon (b) Through tenon with outside wedges (c) Through tenon without wedges (d) Diagonal blind Tenon (e) Diagonal blind tenon (f) Continuous straight tenon (g) Cylinder tenon (h) Oblique tenon.

Figure 4. Variations of mortise-and-tenon joints [30]

f) Finishing[31-33]: Sanding, painting, or varnishing is done to enhance aesthetics and protect the wood from environmental damage. Sanding is used to remove imperfections on walls, ceilings, furniture, floors, etc. Sanding is also used to roughen surfaces so that paint or filler compounds cannot stick easily. Applying varnish to the wood substrate's surface without compromising the sample's aesthetic qualities is made possible by thermally compressing the wood substrate before the varnish coating procedure, as opposed to using the time-consuming sanding method. The "exotic wood look" is nevertheless appealing on the thermally compressed surface[34].

g) Quality Control and Testing[35-38]: Final inspection ensures that the product meets industry standards and customer requirements. The role of QC (Quality Control) cannot be separated from a production process. They are the spearhead or screening of the quality of production results. In the wood industry, the QC position should stand alone, so it is not part of the production structure but is a separate organization that is directly responsible to the director or factory head. If the QC team is placed under production, it is feared (and usually) that there will be a conflict of interest, there will be pressure from the production manager to lower quality standards under the pretext of delivery schedules or other reasons.

3.1.1 Analysis for wood manufacture

To analyze the quality of wood in the manufacturing process, several equations that need to be used include (a) moisture content, (b) mass loss (ML_f), (c) soil moisture content (MC_{soil}), (d) specific gravity, and (e) adhesive strength [39]**.** The formulas used for the determination of the moisture content in the piece of wood are taken from the standard ISO 13061-1 2014 [40]. Two general approaches to determine wood moisture content can be distinguished. In direct measurements, the moisture content is determined by oven-drying or water extraction, whereby both are destructive methods with respect to timber members in-situ. Indirect measurement methods use physical properties of wood which are correlated to the wood moisture content[41], to calculate Moisture Content using the oven dryng kiln method, shown in equation (5), where Mc is moisture content in %; m_1 is the initial mass of the test piece before drying (g); m_2 is the oven-dry mass of the test piece (g). In general, mass loss indicates how much mass is lost compared to the initial mass, which is usually caused by water evaporation, decomposition, gas release, or material degradation. Mass loss is shown in equation (6), where, $m_{0,i}$ is the oven-dry mass before incubation (g); and $m_{0,f}$ is the oven-dry mass after incubation (g).

$$Mc = \frac{m1-m2}{m2} \times 100\% \quad (5)$$

$$ML_f = \frac{mo,i-mo,f}{mo,i} \times 100\% \quad (6)$$

Soil samples of 50–90 g (depending on the soil density) were taken for determining the $MC_{soil.}$ Three replicate samples were taken, weighed to the nearest 0.01 g, oven-dried at 103°C for 24 h, and weighed again. where MC_{soil} is the soil moisture content (%), m_w is the wet soil mass (g); and m_o is the oven-dry soil mass (g). Soil Moisture Content is shown in equation (7). Wood specific gravity test is carried out by utilising a sample measuring its dimensions in an air-dry state (Vku), then it is blended at a temperature of 103+2° C so that the kiln dry weight (Bkt) is obtained. The specific gravity is calculated by the equation (8). Where Bjku is dry wood specific gravity, Bkt is kiln dry weight (g), Vku is volume of air dried (cm^3), R Water is water density at 4°C (g/cm^3)[10]. Specific gravity is shown in equation (8). The amount of stickiness calculated by the equation (9). Where KR = Stickiness (kg/cm^2), A = The area of the sliding plane (cm^2), P = Maximum load (kg) [10].

$$MC_{soil} = \frac{mw-mo}{mo} \times 100\% \quad (7)$$

$$Bjku = \frac{Bkt/Vku}{R\ water} \quad (8)$$

$$KR = \frac{P}{A}\ kg/cm^2 \quad (9)$$

3.1.2 Waste Management

One of the biggest sources of waste in any country is the building sector. Actually, more garbage is produced worldwide by the building industry than by any other single sector of the economy. However, waste has historically been viewed as an unavoidable byproduct of construction and is typically handled more from a health and safety standpoint than with recycling in mind. Research conducted in the United Kingdom found that between 10 and 15 percent of the wood used in new construction is recycled. Policymakers are concerned about this data because it shows that the recycling rate for wood obtained from construction and demolition (C&D) is significantly lower than that of other C&D materials like structural steel (98%) and concrete (82%) [42].

For governments, businesses, and society at large, sustainability of production systems is a major concern, especially in the manufacturing and processing of timber. This sector is well-positioned to offer goods that improve long-term environmental, economic, and social sustainability because its products are made from renewable natural resources found in forests. The following recycling services are usually and occasionally offered for free by the manufacturing companies: Offcuts of solid wood: - firewood or fuel briquettes for heating - charitable organizations (schools, kindergartens, wood turners, and craft clubs); charity plywood offcuts; shavings and sawdust (if uncontaminated): bedding for animals.

Practical steps to reduce waste in the current production process include: using CNC machines; using automated cutting machines to generate finished dimensions specified for the furniture parts; ordering timber and medium-density fiberboard (MDF) boards at specific sizes; designing furniture with simple shapes that don't require excessive machining; outsourcing most processing operations that generate a significant amount of leftover (such as turning, dressing, joint components, and veneer lamination); improving jointing methods by using glues with high bonding performances and waterproof (such as modified urea formaldehyde glue, cross-linked PVA, and polyurethane glue); lightning jointing; finger jointing[43].

The environmental impacts resulting from the disposal of 1 kg of wood waste to a landfill are based on several impact categories. The analysis results show that the global warming category has the largest contribution with a value of 8.37×10^{-2} kg CO_2 equivalent, which indicates a significant role of landfills in greenhouse gas emissions. Other impacts include acidification of 5.35 × 10^{-5} kg SO_2 equivalent and eutrophication of 2.61 × 10^{-3} kg PO_4 equivalent, which have the potential to affect the quality of soil and water around the disposal site. In addition, the impact on ozone layer depletion is relatively small, namely 4.27 × 10^{-9} kg CFC-11 equivalent. From a human health perspective, both the non-carcinogenic and carcinogenic toxicity categories showed low values, at 2.10 × 10^{-9} and 5.95 × 10^{-9} cases, respectively, but still confirmed the potential health risks from landfilling wood waste practices. This narrative emphasizes that landfilling is not an impact-free wood waste management option, so more sustainable management alternatives are needed [44]. Figure 5 shows the MDF wood waste management scenario.

Figure 5. MDF wood waste management scenario adapted from Pinho et al[44].

Based on the research shows that in terms of recovering 1 tonne of wood waste, MDF has the greatest environmental benefit in all of the categories evaluated. This advantage also occurs when the production quantities of MDF are associated with time. MDF stands out as having the highest environmental benefit values for global warming. However, studies that examine yearly production reveal that MDF have more advantages when it comes to the production of bricks and energy. Medium-density particleboard (MDP) can be recycled up to 16 times after use, indicating the potential circularity of these products before they are disposed of in landfills or burned[44].

Indoor wood surfaces don't need to be coated. However, other coatings like paint, lacquer, wax, or oil are frequently applied to the surfaces to enhance their performance and lifespan. Surface coatings frequently lower emissions from the wood substrate, however the coating also releases various compounds. The kind and composition of resins and other agents used in coatings affect emission rates and chemicals released, which highlights the significance of researching and evaluating various coatings prior to installation[45]. There are numerous chances to enhance wood waste management techniques in environmental management. According to ISO 14040, Life Cycle Assessment (LCA) is a method for evaluating a product's environmental effects throughout the course of its life cycle [46]. Wood waste in LCA studies shown in Figure 6.

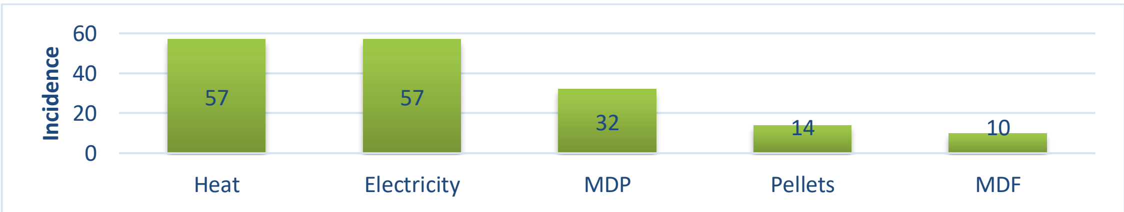


Figure 6. Life cycle assessment studies for MDF and others adapted from Pinho and Calmon [46].

MDF waste management is directed at a strategy for temporary storage of biomass carbon and waste utilization based on material quality through sorting, recycling, controlled combustion, and landfill technologies analyzed in an integrated manner within a single system. From the manufacturing side, this research explores pre-treatment technologies to remove or reduce the urea-formaldehyde resin content in MDF waste to enable its reuse as a secondary raw material or energy source, as well as the application of low-cost additives and optimization of the incineration process to improve environmental performance. In addition, the development of technology-based products, such as plastic wood and magnesium oxide cement (MOC)-based cement panels, is studied as sustainable manufacturing alternatives to replace virgin materials. The cascade use approach is strengthened through an analysis of resource efficiency, the number of tiered use stages, and the integration of material substitution technologies, so that the MDF waste management and manufacturing strategy is not only oriented towards reducing environmental impacts, but also towards increasing added value and the sustainability of the wood-based industry.

3.1.3 Integration of AI Technology in MDF Recycling Process

To improve the efficiency of the MDF waste recycling process, reduce environmental impacts, and optimize the manufacturing process through an artificial intelligence approach, a modular manufacturing system based on Machine Learning was designed. This system consists of five main stages that are integrated with each other and supported by sensory technology, intelligent data processing, and Internet of Things (IoT)-based connectivity. The initial stage is automatic collection and sorting, utilizing cameras and sensors to detect visual characteristics of MDF waste, including paint contamination, resin, and material degradation. Integration CNN (Convolutional Neural Network) model is used to classify waste that is suitable and not suitable for recycling in real-time. The second stage, cleaning and initial processing, adopts environmentally friendly abrasive or chemical pre-treatment to remove contaminants. Clustering models such as K-means are applied to group contamination levels and determine the most appropriate cleaning method adaptively. Furthermore, at the grinding and fiber separation stage, MDF waste is crushed using a hammer mill or refiner to produce fiber. This process is controlled by a regression model that predicts fiber quality based on parameters such as moisture content, density, and residual resin.

In the fourth stage, reformulation and pressing, the resulting fibers are remixed with a bio-resin-based adhesive and processed into new MDF boards through a controlled pressure process. To determine the optimal composition that produces high-strength and low-emission products, optimization models such as Genetic Algorithm and Reinforcement Learning are used. The final stage of the system is quality control and learning feedback, where cameras and sensors inspect the MDF surface and structure for defects. Supervised learning models are then used for defect classification and continuous generation of new training data, which supports iterative improvement of model accuracy. With this system, recycled MDF of standardized quality is produced, predictive reports of material formulation, and energy and raw material efficiency increases by 20-30%. In addition, this system is significantly able to reduce waste that goes to landfills.

As a further development, this system is directed to support cross-industry adaptation through the application of transfer learning, so that it can be used in various factories with minimal adjustments. In addition, the application of LCA based on machine learning will be used to evaluate the environmental impact of each recycling cycle, strengthening the position of this system as a smart technology-based solution in supporting the circular economy and sustainable industrial practices. The manufacturing scheme of MDF waste processing based on machine learning is shown in Figure 7. The design illustrates a systematic and integrated approach to recycling MDF waste efficiently, precisely, and sustainably. This model combines industrial process automation with artificial intelligence to improve the quality of recycled products while minimizing environmental impacts.

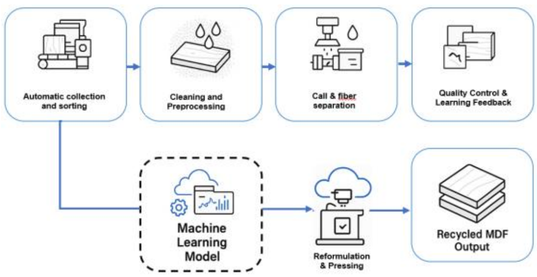


Figure 7. The manufacturing scheme of MDF waste processing based on machine learning

The process begins with the automatic collection and sorting stage, where MDF waste is classified in real-time using visual sensors and computer vision systems. Integration CNN type machine learning model is trained to recognize visual characteristics of waste, such as paint, resin, or surface structure degradation [47-49]. The classified waste will then go through a cleaning and initial processing process, which is designed to remove physical and chemical contaminants.

The third stage is milling and fiber separation, where MDF waste is crushed into fine fibers. Regression models are used to predict fiber quality based on input parameters such as moisture content, initial density, and type of resin used. The results of this prediction are the basis for decision making in the next stage. Input from the prediction model will be used in the reformulation and pressing stage, namely the process of re-engineering MDF fibers by adding new bio-material-based resins or magnesium oxide cement (MOC). The reinforcement learning or genetic algorithm type of Machine Learning model is used to optimize the mixing and pressure parameters in the pressing process to produce MDF with the best quality and minimum emissions.

The last stage is quality control and learning feedback. The final product is analyzed using a computer vision-based automatic inspection system to detect physical defects. The defect data collected is used to retrain the model in a closed-loop system, forming an adaptive and continuous learning manufacturing process. Overall, this system shows significant potential in increasing the efficiency of MDF waste utilization, reducing environmental burdens, and producing recycled products with quality that can be equated with new materials. This approach is in line with the principles of the circular economy and industry 4.0, and opens up new space for the application of machine learning in the biomass-based material processing sector.

3.2. Analysis of bookshelf design performance

The research was conducted by designing and simulating von Mises stress and safety factor on a bookshelf to determine its structural performance. The design of the bookshelf was subjected to a maximum load of 10 kg. The bookshelf was designed with 5 layers for interior use to enhance the aesthetic value of a building space. The results of the MDF structural simulation are shown in Figure 8.

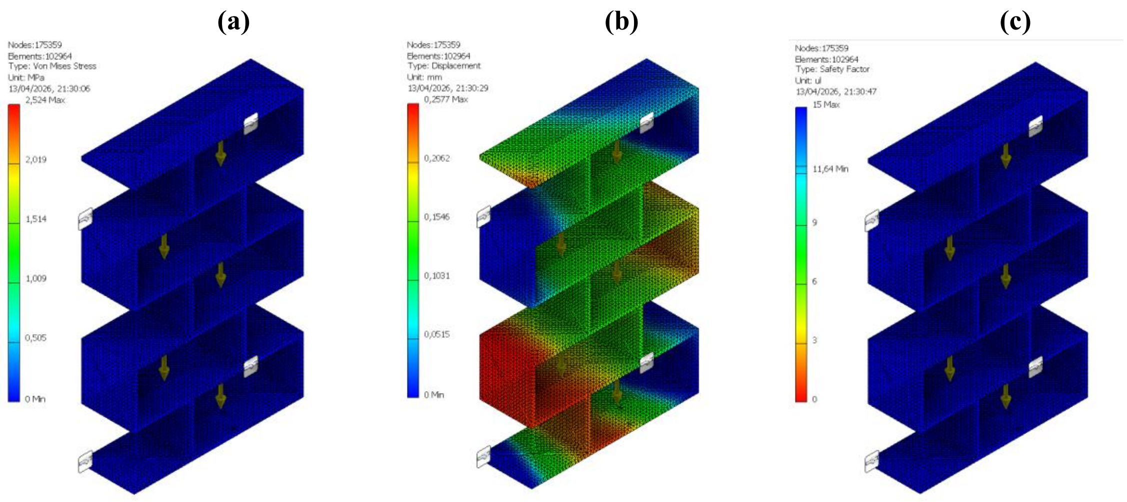


Figure 8. Performance of bookshelf using MDF:
(a) von mises stress; (b) displacement; (c) safety factor

The analysis results show that the Von Mises stress distribution on the MDF bookshelf has a maximum value of 2.254 MPa, indicating that the structure is still well below the material's strength limit. The displacement value is very small, at 0.2557 mm, so the deformation is insignificant and does not affect the shelf's structural function. The simulation results show that the critical part is in the second layer from the bottom. The simulation results are shown in the Table 3.

Table 3. Simulation Results

Stress Analysis	Von Misses Stress (MPa)	Displacement (mm)	Safety Factor
Min	0.000	0.000	11.64
Max	2.254	0.2557	15

The higher deformations at the top and bottom of the shelves are generally caused by the load distribution and support conditions of the structure. The upper section experiences greater deformation due to the load, resulting in deflection due to the gravitational force acting on the panel span. Meanwhile, the lower section also exhibits high deformation because it serves as the primary support, supporting the accumulated load from all levels of the shelves, resulting in stress concentration.

4. Conclusion

This study indicates that the sustainable wood manufacturing process in the industry plays a crucial role in ensuring the quality of the final product, production efficiency, and environmental sustainability. Based on the waste management aspect, this study reveals that the life cycle assessment (LCA)-based approach shows that MDF is the most environmentally friendly wood waste management scenario. Recycling strategies, solid waste reuse, and waste-to-energy processing are important steps in creating a sustainable wood manufacturing process. The performance of a bookshelf design made from MDF has a good safety factor. This design can be implemented for building interiors. Bookshelf manufacturing can be carried out using an integrated manufacturing approach with artificial intelligence for process efficiency.

It is advised to create an AI and IoT-based quality monitoring system that can identify irregularities from the start of production in order to increase productivity and sustainability in the wood manufacturing process. Wood waste should be processed into value-added goods like MDF or biomass in order to implement a circular economy strategy. Machine learning and thermal simulation can also be used to optimize MDF-based products and anticipate wood life. In order to support technology-based sustainable wood production strategies, more attention should be paid to economic and social studies as well as research on substitute materials such bio-resins.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (OpenAI) in order to improve the clarity and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author would like to thank the Faculty of Engineering, Universitas Negeri Semarang (UNNES) for funding this research under the Research and Development (Faculty) scheme.

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