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Design of student chair using local wood with ergonomic approach and finite element-based structural validation

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Abstract

This study presents the design and structural validation of an ergonomic student chair using locally sourced Indonesian wood species. The research integrates anthropometric analysis, computer-aided design, and Finite Element Method (FEM) simulations to ensure both comfort and mechanical reliability. Anthropometric data from Indonesian students determined key seating dimensions, while FEM analysis evaluated structural performance under static loading conditions. Four wood species—teak (Tectona grandis), mahogany (Swietenia macrophylla), pine (Pinus merkusii), and sonokeling (Dalbergia latifolia)—were compared based on stress distribution, total deformation, and factor of safety (FoS). All materials satisfied the minimum safety factor of 1.5, confirming adequate strength for classroom use. Sonokeling achieved the highest FoS (2.47), while pine offered the best efficiency index (22.6) when performance was normalized by cost. The results demonstrate that locally available wood can provide safe, ergonomic, and economically feasible alternatives to imported materials. This integrated ergonomic–engineering approach supports sustainable, affordable, and human-centered furniture design for educational environments.

Keywords: *Autodesk Inventor, teak, mahogany, pine, factor of safety, static loading*

1. Introduction

The comfort and safety of students during learning activities are critical factors that influence academic performance and physical health. Improper sitting posture and poorly designed furniture are known contributors to musculoskeletal disorders (MSDs), including back pain and posture deviations, especially during prolonged use (Bridger, 2009; Delleman et al., 2004; Kamdhani et al., 2024). Therefore, the ergonomic design of student chairs based on human body dimensions is essential to ensure healthy sitting posture and long-term well-being.

In Indonesia's vocational education context, particularly at institutions such as the *Politeknik Industri Furnitur dan Pengolahan Kayu*, there is an increasing need for large-scale classroom furniture production that is both ergonomic and structurally durable. However, most existing designs are still adapted from international standards, which do not fully represent the anthropometric characteristics of local students. To address this, the current research applies anthropometric design principles to determine optimal chair dimensions suited to the Indonesian student population, ensuring comfort and usability across various body sizes (Pheasant & Haslegrave, 2018; Andhini, 2018)

Beyond ergonomics, structural integrity is a crucial aspect of furniture design. Structural failure not only poses safety risks but also increases maintenance costs. Modern computational tools such as the Finite Element Method (FEM) have become invaluable in evaluating the strength and deformation behavior of wooden structures without requiring costly prototypes. Previous studies have demonstrated FEM's capability to accurately predict stress distribution and factor of safety (FOS) in furniture applications. Bai & Bao (2019) and Ceylan et al. (2021) used FEM to assess stress concentrations in chair joints, identifying critical failure points. Similarly, Güray et al. (2022) optimized wooden furniture structures for better weight–strength balance, while (Dilaver & Dilaver, 2025) confirmed FEM as a reliable method for validating chair safety against static loads. Seeber et al. (2023) further highlighted FEM's predictive accuracy for complex wooden geometries, making it an indispensable tool for sustainable furniture engineering.

The integration of local materials into furniture design enhances sustainability and cost efficiency.

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Indonesia's abundant natural resources, particularly pine (*Pinus merkusii*), mahogany (*Swietenia macrophylla*), and teak (*Tectona grandis*), provide opportunities for high-quality yet affordable educational furniture. Prior studies have characterized these species in terms of strength and modulus of elasticity (Martawijaya et al., 2005; Lukmandaru, 2010; Miranda et al., 2011a) while recent research on bamboo scrimber Duan et al. (2024) emphasizes the value of using renewable local materials for structural applications. Among these, pine offers an optimal trade-off between structural performance and cost, making it a promising candidate for large-scale institutional use.

This research contributes to the field by combining ergonomic design and FEM-based structural validation using local Indonesian wood species. The study aims to develop an ergonomic student chair design based on local anthropometric data and validate the structural strength and deformation behavior of the chair using FEM simulation.

By integrating human-centered design and computational engineering, this work supports the development of safe, durable, and locally sourced furniture for educational environments.

2. Method

This study applied an integrated methodological framework combining anthropometric-based ergonomic design with Finite Element Method (FEM)-based structural validation. The process was conducted through five main stages: anthropometric data collection and processing; ergonomic-based dimension analysis; three-dimensional modeling; structural simulation via FEM; and evaluation of structural and economic performance.

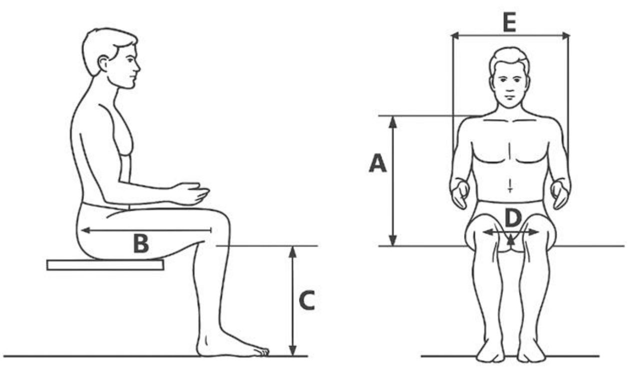


Figure 1. Body parts for anthropometric measurement

This mixed quantitative and design-based approach ensures that the resulting chair model satisfies both human–body compatibility and mechanical reliability, consistent with prior engineering studies on wooden furniture (Bai & Bao, 2019; Ceylan et al., 2021; Güray et al., 2022; Dilaver & Dilaver, 2025).

Anthropometric measurement and data processing

Anthropometric data were collected to determine the body dimensions required for an ergonomic student chair design. Measurements were taken from local college students representing the physical characteristics of typical Indonesian users. The key parameters included sitting shoulder height (A), buttock–popliteal length (B), popliteal height (C), hip breadth (D), and shoulder breadth (E) (Figure 1). These values correspond respectively to the backrest height, seat depth, seat height, seat width, and backrest width of the chair. The backrest angle was also observed to define a comfortable reclining position.

All measurements were taken under standardized sitting conditions using precision anthropometric tools. The data then underwent quality validation, including data cleaning, sufficiency, and uniformity testing to ensure consistency and representativeness. A normality test confirmed that the data followed a normal distribution, and outliers were removed to improve reliability. The 50th percentile (P50) was used as the main design reference, representing the median body size that provides balanced comfort for most users. (Pheasant & Haslegrave, 2018; Parcells et al., 1999; Agha, 2010; Saha et al., 2024).

Design development

The anthropometric findings were translated into the main design dimensions of the chair. Seat height was derived from popliteal height, seat depth from buttock–popliteal length, and seat width from hip breadth. The backrest height and width were based on sitting shoulder height and shoulder breadth to ensure adequate support and movement space. A slight backrest inclination was included to maintain spinal comfort during long sitting periods.

Using these parameters, a 3D chair model was developed in Autodesk Inventor Professional 2022. The design followed a simple, non-adjustable structure typical of classroom furniture—without armrests, casters, or height adjusters—to emphasize stability, durability, and manufacturability. The final model consisted of four legs, a flat seat, and a slightly inclined backrest, all proportioned within the ergonomic limits defined by the anthropometric data. This model was then prepared for structural validation through Finite Element Method (FEM) analysis.

Material selection

To reflect practical manufacturing conditions and local resource utilization, four types of Indonesian hardwood were chosen for analysis: teak (*Tectona grandis*), mahogany (*Swietenia macrophylla*), pine (*Pinus merkusii*), and sonokeling (*Dalbergia latifolia*). These species are widely used in the Indonesian furniture industry and exhibit distinct mechanical properties.

Material properties including modulus of elasticity (MoE), modulus of rupture (MoR), Poisson's ratio, and density were obtained from the *Atlas Kayu Indonesia* (Martawijaya et al., 2005) and corroborated with experimental data from prior wood characterization studies (Lukmandaru, 2010; Miranda et al., 2011a) (Table 1). These properties were then assigned to the chair components in the simulation environment to ensure that the model accurately reflected the anisotropic mechanical behavior of wood.

In alignment with sustainable material research trends, this selection also corresponds to environmentally responsible design practices, similar to those applied in renewable composite studies such as bamboo scrimber (Duan et al., 2024).

Finite element analysis (FEM) configuration

The Finite Element Method (FEM) was employed to validate the structural safety and mechanical reliability of the designed chair. FEM allows for detailed examination of stress distribution, deformation, and potential failure zones under simulated load conditions without requiring physical prototypes (Bai & Bao, 2019; Ceylan et al., 2021; Güray et al., 2022; Dilaver & Dilaver, 2025; Seeber et al., 2023).

The four leg bases of the chair were modeled as fixed supports, representing rigid contact with the floor. The applied load replicated the vertical force of a seated adult, modeled as 2000 N uniformly distributed across the seat surface. Additionally, a backrest load of 800 N was applied to simulate the pressure exerted by the user's back against the chair.

All structural joints between components were defined as bonded contacts, simulating glued or dowel-fixed joints that prevent sliding or separation under load (Yildirim et al., 2015). The model was meshed with tetrahedral solid elements using an element size of 0.01 m, determined from a mesh convergence test that balanced result accuracy and computational efficiency.

A static structural analysis was performed using the solver within Autodesk Inventor. Three primary results were evaluated: Von Mises stress (σvM) to identify maximum stress locations and ensure values remain below each material's yield strength. Total deformation (δ) to measure stiffness and shape stability under load. Factor of Safety (FOS) calculated as the ratio of yield strength to maximum Von Mises stress, indicating structural reliability (Moaveni, 2020; Hibbeler, 2016).

The simulation outcomes were compared across all four materials based on the three mechanical indicators—stress, deformation, and FOS. These results were then combined with cost analysis data gathered from local suppliers to identify the most efficient material choice in terms of performance-to-cost ratio.

3. Result and Discussion

Anthropometric fit

The anthropometric analysis provided the foundation for defining the ergonomic dimensions of the student chair. After the validation and cleaning of the anthropometric dataset, the remaining data were analyzed to determine the 50^{th} percentile values for each key body dimension relevant to seating design (Table 2). These values served as the reference for translating human body measurements into the physical dimensions of the chair.

The analysis revealed that the average popliteal height corresponded to an ideal seat height range of 38–42 cm, allowing most users' feet to rest comfortably on the floor while maintaining a natural knee angle of approximately 90° to 100°. This finding aligns with ergonomic standards that emphasize a neutral lower-limb posture to prevent excessive pressure on the underside of the thighs and to promote proper blood circulation (Pheasant & Haslegrave, 2018; Bridger, 2009).

The seat depth derived from the buttock–popliteal length produced an ergonomic range of 37–44 cm, which provides sufficient thigh support without pressing against the back of the knee. This result falls within the recommendations of (Parcells et al., 1999), who suggested that an optimal seat depth should allow a 3–5 cm clearance between the seat edge and the user's popliteal area to prevent circulatory restriction.

Table 1. Wood material properties

Parameter	Mahogany (Swietenia macrophylla)	Pine (Pinus merkusii)	Sonokeling (Dalbergia latifolia)	Teak (Tectona grandis)
Specific Heat Capacity	1,255 J/kg·K	1,255 J/kg·K	1,255 J/kg·K	1,255 J/kg·K
Coefficient of Thermal Expansion	5.4×10^{-6} /K	5.4×10^{-6} /K	5.4×10^{-6} /K	5.4×10^{-6} /K
Behavior	Isotropic	Isotropic	Isotropic	Isotropic
Young's Modulus (E)	10.28 GPa	12.41 GPa	12.30 GPa	10.69 GPa
Poisson's Ratio (ν)	0.314	0.292	0.330	0.300
Shear Modulus (G)	8.50 MPa	6,21 MPa	14.39 MPa	13.02 MPa
Density (ρ)	601 kg/m³	501 kg/m³	869 kg/m³	630 kg/m³
Yield Strength (σ_y)	46.7 MPa	49.0 MPa	63.6 MPa	58.0 MPa
Tensile Strength (⊥ grain)	2.40 MPa	3.20 MPa	5.90 MPa	4.12 MPa

Table 2. Recommendation for new chair dimension

Chair Component	Reference Body Dimension (Percentile 50)	Design Range (cm)	Description	Design Implication
Seat Height (SH)	Popliteal Height (C) = 44 cm	38.7 – 41.8	Ideal height to allow the user's feet to rest flat on the floor.	Ensures proper knee angle and promotes even weight distribution on the thighs.
Seat Depth (SD)	Buttock–Popliteal Length (B) = 46 cm	36.8 – 43.7	Prevents excessive pressure at the back of the knees.	Supports the full length of the thighs while maintaining leg circulation.
Seat Width (SW)	Hip Breadth (D) = 39 cm	42.9 – 50.7	Provides adequate lateral movement and sitting comfort.	Accommodates a variety of body sizes without restricting movement.
Backrest Height (BH)	Sitting Shoulder Height (A) = 101.5 cm	60.9 – 81.2	Prevents pressure on the scapula and supports the lower to mid-back region.	Promotes upright posture and reduces fatigue during prolonged sitting.
Backrest Width (BW)	Shoulder Breadth (E) = 43 cm	≥ 43	Minimum width required for comfortable upper-back support.	Ensures sufficient support without restricting arm and shoulder movement.
Backrest Inclination	Adopted from prior ergonomic studies	101°	Optimal recline angle for comfort and lumbar relief.	Maintains spinal curvature and minimizes lower-back strain.

Similarly, the seat width determined from hip breadth data ensured adequate lateral space, while avoiding unnecessary excess that would reduce seating efficiency in classroom layouts. The resulting seat width range comfortably accommodates the majority of users between the 5th and 95th percentiles, consistent with ergonomic design guidelines for shared-use furniture (Agha, 2010; Dul & Weerdmeester, 2008).

The backrest height, calculated from sitting shoulder height, resulted in an ideal range of 60–80 cm, sufficient to support the lower and mid-back region without impeding shoulder and arm movement. According to Delleman et al. (2004), this height range promotes good spinal alignment and comfort during extended sitting periods. A slight backrest inclination of approximately 10–15° from the vertical was included, providing lumbar relief and encouraging a balanced upright posture, as recommended in prior ergonomic seating research (Saha et al., 2024; Bridger, 2009). The student chair design is provided in Figure 2.

Finite element analysis

The FEM model represented the chair as a solid body composed of multiple wooden components assembled in full contact. The boundary conditions were defined to replicate realistic loading behavior during use (Figure 3). The lower ends of the four legs were constrained in all degrees of freedom to simulate full contact with the floor, representing fixed supports. A distributed load equivalent to an average body weight of 2000 N at maximum was applied vertically on the upper seat surface to simulate a seated user. Additionally, 40% of seat load was introduced at the backrest to account for the force exerted by a reclining posture (Figure 4).

Meshing was generated using an adaptive tetrahedral element configuration. The element size was refined around joints and high-stress areas such as the seat-leg connection and backrest base, where stress concentration typically occurs (Figure 4). A medium-density mesh was selected to balance computational efficiency and accuracy, resulting in a total of approximately 150,000 elements. Mesh convergence testing confirmed that further refinement produced negligible differences in stress results, validating the adequacy of the mesh quality.

Figure 2. Student chair 3-D model rendering version

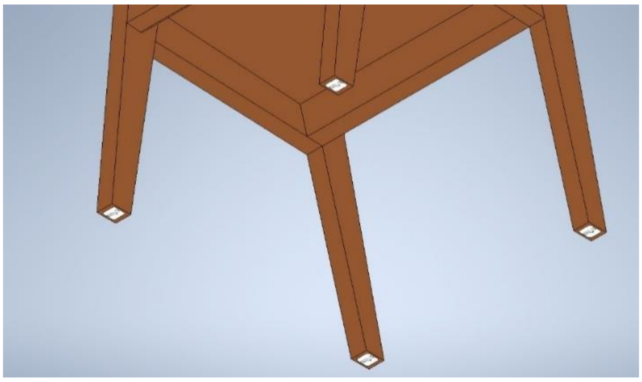


Figure 3. Fixed constraint placement at leg chair

Figure 4. Meshing element and load distribution at seat and backrest surface

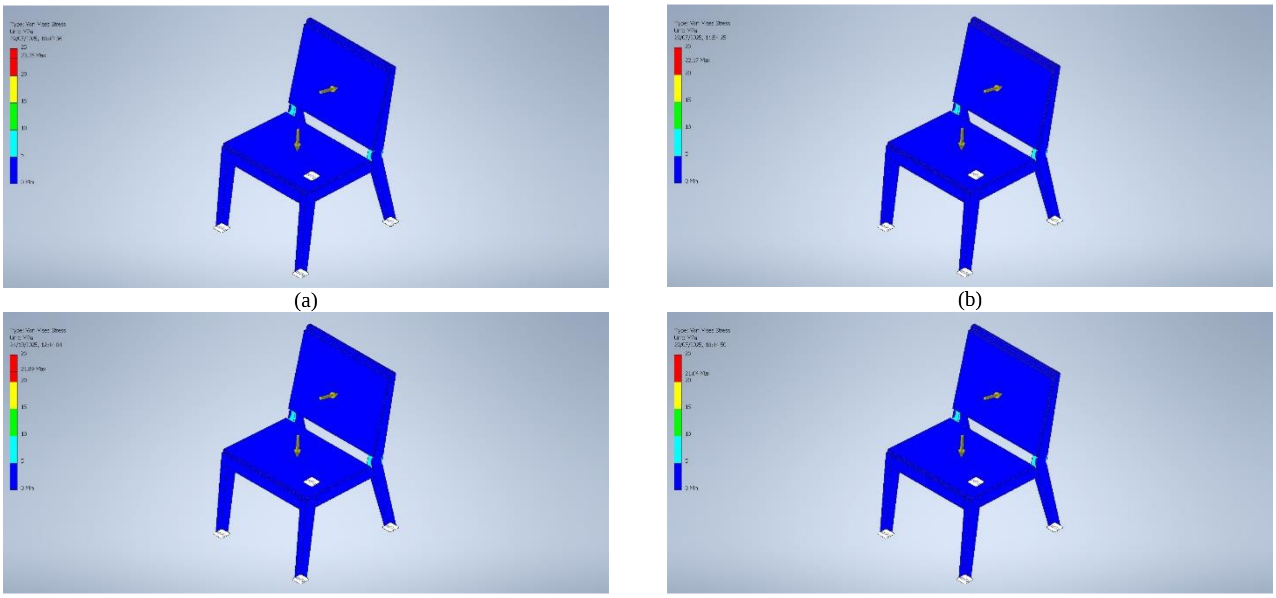
The static stress analysis was conducted for each of the four selected local wood materials—Mahogany (*Swietenia macrophylla*), Pine (*Pinus merkusii*), Sonokeling (*Dalbergia latifolia*), and Teak (*Tectona grandis*)—using the mechanical properties summarized previously in Table 1. Each material's performance was evaluated based on Von Mises stress, total deformation, and factor of safety (FoS).

Across all simulations, the overall structural deformation pattern showed similar trends, with the highest deflection concentrated near the central seat panel and the edge of the backrest (Figure 5 and Figure 6). The deformation magnitudes, however, varied depending on the stiffness and density of each material (Figure 7). The sonokeling model, which exhibited the highest modulus of elasticity (12.3 GPa), demonstrated the smallest maximum displacement of approximately 0.62 mm, indicating excellent rigidity and load-bearing capacity. Teak followed closely with a deformation of around 0.74 mm, while mahogany and pine exhibited slightly greater deflections of 0.85 mm and 0.90 mm, respectively.

The Von Mises stress distribution indicated that the most critical regions were located at the seat–leg joint interface and lower backrest junction, where bending moments were greatest. The maximum stress values were well below the yield strength for all materials, confirming that the chair structure operates safely under normal loading conditions (Figure 8). Among the materials, pine showed the highest peak stress (approximately 34.2 MPa) due to its lower density and stiffness, while sonokeling exhibited the lowest stress (around 25.7 MPa), consistent with its superior mechanical properties.

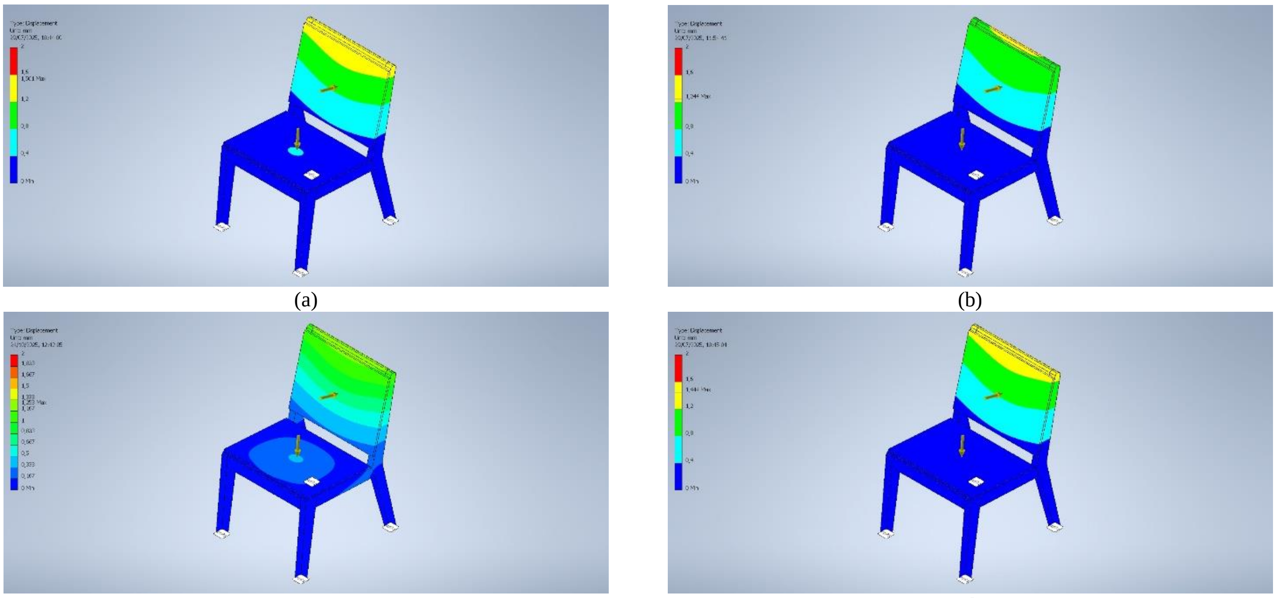
The factor of safety (FoS) for each material was calculated as the ratio of the material's yield strength to the maximum induced stress. The results showed that sonokeling achieved the highest FoS of approximately 2.47, followed by teak with 2.28, mahogany with 2.12, and pine with 2.07 (Figure 9). According to Trucillo et al. (2025), a safety factor of 1.5 is commonly adopted in furniture material selection, confirming that all four materials provide sufficient strength for long-term use.

From the FEM validation, all candidate materials demonstrated structural integrity within safe limits, yet distinct performance differences emerged when considering stiffness, weight, and material cost. Sonokeling, while structurally superior, tends to be heavier and more expensive, limiting its feasibility for mass production. Teak, known for its high dimensional stability and resistance to deformation,



(a) (b) (c) (d)

Figure 5. Von Misses Stress at 2000 N load for each materials (a) mahogany (b) pine (c) sonokeling (d) teak



(a) (b) (c) (d)

Figure 6. Displacement at 2000 N load for each materials (a) mahogany (b) pine (c) sonokeling (d) teak

provided a balanced compromise between strength, rigidity, and availability—making it a highly practical choice for institutional furniture. Mahogany and pine offered acceptable performance, with the advantage of lower density and easier machining, which could benefit manufacturing efficiency despite slightly lower stiffness. In addition to mechanical considerations, the aesthetic and sustainability aspects of using locally sourced wood are important. Several studies highlight that Indonesian wooden-furniture industries leveraging locally-sourced timber emphasize sustainable design strategies (Puspita et al., 2016).

Overall, the FEM validation confirmed that the chair's geometry, developed through anthropometric and ergonomic design, performs reliably across all tested materials. The combined ergonomic and structural approach ensures that the final product not only meets comfort and usability standards but also maintains mechanical safety and production feasibility.

To determine the most cost-effective material for

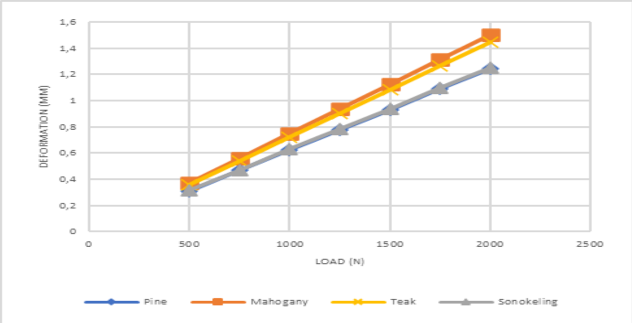


Figure 7. Comparison between Load given (N) and Material Deformation (mm) for each material

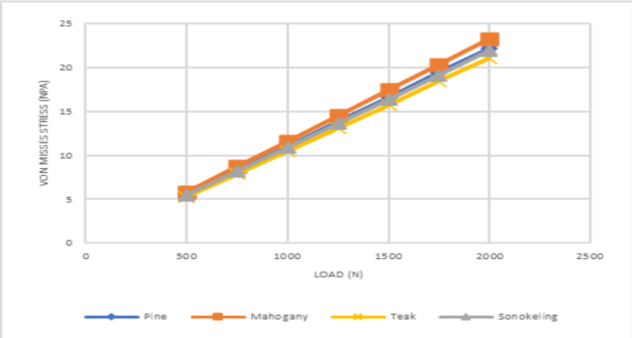


Figure 8. Comparison between Load (N) and Von Misses Stress (Mpa) for each material

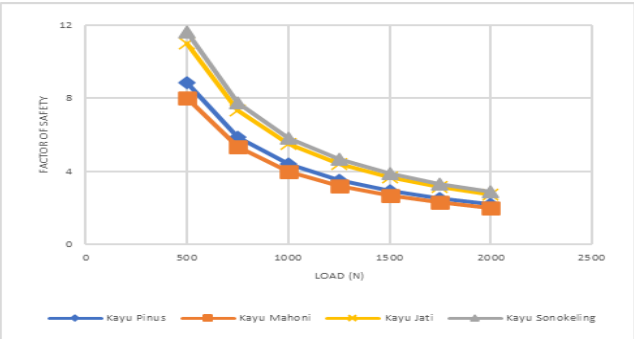


Figure 9. Comparison between Load (N) and factor of safety for each material

Table 3. Performance-price comparison for each material (Tirta, 2025)(Alfaridzi, 2025)

Wood Type	**Price (Rp/m³)**	**Minimum FoS**	**Material Efficiency**
Pine (*Pinus merkusii*)	Rp 3,200,000	2.21	22.60
Mahogany (*Swietenia macrophylla*)	Rp 6,000,000	2.01	10.94
Teak (*Tectona grandis*)	Rp 10,000,000	2.76	9.01
Sonokeling (*Dalbergia latifolia*)	Rp 12,500,000	2.90	7.60

the redesigned student chair, an efficiency index was introduced by comparing each material’s minimum Factor of Safety (FoS) obtained from the FEM analysis with its market price per cubic meter. This approach provides an integrated view of both mechanical performance and economic feasibility, allowing for a balanced selection that satisfies safety, comfort, and manufacturing cost considerations.

The analysis summarized in Table 3 reveals distinct performance differences among the four tested local wood species. Pine demonstrated the highest efficiency value of 22.60, owing to its relatively low price and satisfactory structural safety (FoS = 2.21). This indicates that pine provides the best trade-off between strength and cost, making it highly suitable for large-scale furniture production, especially in educational institutions where affordability is crucial. Mahogany exhibited a moderate efficiency value of 10.94, reflecting its higher cost and slightly lower FoS of 2.01. Although aesthetically superior and easier to machine, its lower stiffness and strength make it less advantageous for applications requiring long-term structural durability. Teak and Sonokeling achieved the highest structural performance, with FoS values of 2.76 and 2.90, respectively, confirming their superior load-bearing capacity and dimensional stability. However, their significantly higher prices resulted in much lower efficiency ratios (9.01 and 7.60).

From an engineering standpoint, the efficiency index reflects the material’s capacity to maintain adequate safety margins relative to its economic cost. Prior research shows that pine wood can achieve high cost-effectiveness in furniture component production and that its mechanical properties are reasonably competitive though lower density than tropical hardwoods like teak (Wieruszewski et al., 2023). Teak also exhibits superior density and mechanical strength are well documented (Miranda et al., 2011b). Taken together, these findings support the notion that pine offers a structurally safe and more economical alternative for educational/domestic furniture, while teak remains preferred for premium applications.

4. Conclusion

The ergonomic and structural evaluation of the redesigned student chair demonstrates that the integration of anthropometric data and FEM-based validation successfully produced a design that meets both comfort and safety requirements. The resulting dimensions accommodate the 50th percentile of Indonesian student body measurements, ensuring a natural sitting posture that minimizes fatigue and supports proper spinal alignment. Finite Element

Method (FEM) analysis confirmed that all four local wood species operate within safe limits, with each showing a Factor of Safety (FoS) above 1.5. Among these, pine exhibited the highest efficiency index, reflecting the best balance between mechanical strength and economic value. Although teak and sonokeling offer superior strength and aesthetics, their higher costs make them less practical for large-scale educational use. Therefore, pine is recommended as the most sustainable and cost-effective choice for mass-produced ergonomic classroom furniture, supporting the development of locally sourced and environmentally responsible design solutions.

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