Quality Improvement in Meranti Plywood Manufacturing Using Six Sigma DMAIC and the Seven Basic Quality Tools

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The plywood industry must maintain strict standards of quality if it is to survive the global market competition and be sustainable in terms of resources. In this paper, a quality assessment of meranti (*Shorea* spp.) plywood in Indonesia is reported, based on QC records from January–December 2024 covering 188,015 panels, which employs the integrated Six Sigma DMAIC and the Seven Quality Tools. The study highlights the major defects responsible for production losses, including insufficient core, thinness, blistering, press marks, and brittleness. An assessment of the performance through Sigma level calculation showed a value of 3.1, computed from the DPMO using five defect opportunities per panel and the conventional 1.5 sigma shift. The use of Fishbone Diagrams and P charts (included in the Results) helped identify process instability and highlight root cause patterns related to machine calibration, operator performance, and thermal variation. Proposed improvements include a proactive maintenance schedule and standardized SOPs for adhesive application and pressing. This approach can be used to scale up yield and quality in the wood-based industry.

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INTRODUCTION

Demand for plywood and engineered wood panels continues to increase, driven by expansion in construction and furniture industries (Cordier *et al.* 2025). Particularly, plywood is valued for its high strength to weight ratio and versatility in structural and non-structural applications. Indonesia is one of the world's leading producers and exporters of plywood, consistently ranking among the top three globally according to FAO forestry production statistics (Hildebrandt *et al.* 2017; Ding *et al.* 2022; Müller *et al.* 2023). The core material being used by this industry is meranti, *Shorea* spp., which is considered one of the most important timber species, renowned for its homogeneous texture, favorable workability, and mechanical properties for the production of the highest quality veneers (Wahyudi and Sitanggang 2016; Puruwita and Oktora 2019; Supriadi *et al.* 2020; Malau *et al.* 2022).

The PT Kayu Lapis Indonesia (KLI) company is one of the leading producers of meranti plywood, manufacturing products of 2.7 mm and 9 mm thickness. Nonetheless, quality consistency during mass production entails one of the greatest challenges in the company. QC records from January to December 2024 indicate that defect rates reached 6.2% across both product lines, contributing to substantial rework and material loss. Fluctuations in raw materials, equipment, and levels of human resource efficiency may lead to quality flaws such as delamination, overlaps, and thickness variation (*i.e.*, out of spec thickness), affecting the product market value and causing the wastage of precious natural resources (Widyastutik and Arianti 2014; Sutiawan *et al.* 2020; Müller *et al.* 2023). This occurs in an age of under increasingly stringent environmental regulations and traceability requirements.

Glue spread is one of the most critical parameters influencing veneer bonding quality in plywood manufacturing. Insufficient adhesive application can lead to core gaps, delamination, and blistering, while excessive glue increases cost and may cause surface defects. Previous studies have shown that optimal glue spread typically ranges between 180 and 220 g/m², depending on veneer species and moisture content, and that variability in glue application is strongly associated with increased defect rates (Ross 2010; Ding *et al.* 2022). Accurate measurement using calibrated scales and routine monitoring are therefore essential for maintaining consistent bond performance.

Hot press temperature is another key determinant of bonding integrity, as it governs adhesive curing, heat transfer, and panel consolidation. Press temperatures outside the recommended window (typically 110°C ± 5°C for meranti-based plywood) have been linked to blistering, brittleness, and incomplete curing, especially under fluctuating moisture conditions. Several studies have demonstrated that maintaining stable press temperature profiles significantly reduces bonding defects and improves mechanical performance, and Six Sigma-based optimization has been applied in related wood composite industries to minimize thermal variation (Minh *et al.* 2024; Flores *et al.* 2025).

The traditional quality control approach, which is based to a great extent on visual observation and human judgment, is no longer adequate for complex modern manufacturing processes. If it is to be both competitive and sustainable, it is necessary for industry to adopt systematic, data-driven approaches to problem-solving that are more proactive rather than reactive. The Six Sigma approach to quality improvement, using its associated DMAIC process (Define, Measure, Analyze, Improve, Control), can be applied as a structured approach to eliminating sources of variability and destructive defects (Germanova-Krasteva and Dimcheva 2020; Koh and Singgih 2021; Dahlia *et al.* 2024; Lubis *et al.* 2025). In modern plywood manufacturing systems, such data-driven approaches typically rely on quantitative measurements such as veneer moisture content tests, glue spread weight monitoring, press temperature logging, and thickness gauging, which together provide a numerical basis for statistical quality analysis. When coupled with the associated "Seven Tools" of quality, such as Pareto Charts, Fishbone Diagrams, and Control Charts, it supplies a potent analytical tool for the visualization of process behaviors as well as identifying CTQ (critical to quality) characteristics, where CTQ characteristics are the measurable attributes that define product acceptability (Pragastio *et al*. 2023). It is the Six Sigma approach that supplies strategy, while the "Seven Tools" supply tactics. The foundational role of the Seven Quality Tools in supporting tactical problem solving is also widely recognized in classical QC references (*e.g.*, Montgomery, *Statistical Quality Control*).

This study aimed to assess and improve meranti plywood quality at PT KLI by integrating Six Sigma DMAIC with the Seven Quality Tools. The study sought systematically to find and reduce the most frequent defects in production, which can also increase yield and reduce waste to global quality standards. The findings provide a scalable model for operational excellence and sustainability within the wider wood-based industry.

MATERIALS AND METHODS

An integrated quality improvement approach is used in this research, which merges the Six Sigma (DMAIC) model and the seven tools of quality to detect, scrutinize, and decrease defects in meranti plywood manufacture systematically. A case study was conducted combining QC database analysis and field observations, structured using DMAIC and the Seven Quality Tools (Dahlia *et al.* 2024; Yi *et al.* 2024; Pragastio et al. 2023; Romdloni and Nuruddin, 2025). PT Kayu Lapis Indonesia (KLI) is one of the major plywood producers in Indonesia, operating at a scale that places it among the largest manufacturers in the sector. Thus, a well-organized approach based on data is required to ensure that the quality improvements are not only quantifiable but also long-lasting.

The study was carried out at PT Kayu Lapis Indonesia (KLI), Mororejo Village Kaliwungu Kecamatan, Kabupaten Kendal, Jawa Tengah. Two main lines of production were examined:

- Thin-plywood line (2.7 mm thickness)
- 9-mm thick plywood line

The above two product types are the company's core export items and provide a considerable share of production. The plant operates two production lines with a combined annual capacity of approximately 188,000 panels, running two shifts per day. These plywood products are core export items for markets governed by standards such as JAS, EN, and CARB, providing a basis for selecting CTQ characteristics aligned with key market requirements. Since quality abnormalities in such items can have direct financial impact on company performance, raw material usage, and customer satisfaction (Puruwita and Oktora 2019; Malau *et al.* 2022; Susanti 2023). The first round of data was collected between September and October 2025 to cover a reasonably sound production condition and defect influence. The quantitative analysis in this study is based solely on the full year QC database from January to December 2024, which provides defect counts and supports the calculation of DPU, DPMO, and Sigma levels. Meanwhile, the September–October 2025 field observations were conducted only to document operational conditions and support the interpretation of root causes. They were not included in the statistical calculations.

Tools and Materials

This study used the full year Quality Control (QC) database from January to December 2024, comprising 188,000 plywood panels from two production lines and documenting monthly production volumes, defect types, and defect frequencies. Statistical analysis and charting were conducted using Microsoft Excel and Minitab, including Pareto charts, P charts, and descriptive statistics to quantify defect patterns and Sigma performance. Field observations conducted in September to October 2025 provided qualitative insights into machine operation, environmental conditions, and operator practices, supporting the interpretation of root causes but not contributing to the quantitative calculations. The CTQ characteristics used in this study were derived from the company's internal product specifications and QC acceptance criteria, which are developed and maintained under ISO 9001:2015 quality management system procedures.

Integrated Data Collection and Analytical Framework

The field observations were conducted over a two-week period in September to October 2025, covering both day and night shifts to capture variation in operating conditions. Each visit followed a structured observation protocol that included a defect check sheet, photographic documentation of machine settings and panel conditions, and daily observation logs. These qualitative outputs were used to support the interpretation of root causes but were not included in the quantitative calculations. While photographic documentation supported qualitative interpretation, all Six Sigma calculations were based exclusively on numerical QC data, including defect counts, production volumes, moisture readings, glue spread measurements, and press temperature logs. The exact procedure of data gathering in this research project was done through direct field observations and secondary documentation to arrive at a complete understanding of the plywood production process at PT Kayu Lapis Indonesia (Gozali *et al.* 2020; Jou *et al.* 2022; Flores *et al.* 2025). The direct observation that was made on the production flow started with the log pond, peeling, drying, gluing, hot pressing, cutting down, polishing, and finally checking the ways in which the machines were running, behavior of the operators, environmental conditions, and handling materials (Minh *et al.* 2024; Pragastio et al. 2023; Ramos-Maldonado *et al.* 2025). Each defect record in the QC database represents a single defect instance identified on an individual plywood panel. A panel may contain more than one defect, and therefore multiple records can be associated with the same panel. To ensure consistency, all defect descriptions were standardized into a unified taxonomy of fourteen defect types based on internal QC terminology. Duplicate entries were removed, and panels with multiple defects were retained as separate defect occurrences for DPU and DPMO calculations. This preprocessing ensured that defect counts, categories, and Sigma metrics were based on a consistent and non-overlapping classification system.

Meanwhile, supporting these observations, the secondary data obtained from the QC records of the company were needed, including annual production volumes, types of defects, and frequencies of defects for the year 2024. To clarify the structure of the dataset used in this study, all quantitative analyses, including DPU, DPMO, Sigma level, Pareto charts, and control charts, were derived exclusively from the full year QC database from January to December 2024. The individual plywood panel served as the primary sampling unit, and each panel could contain zero, one, or multiple defects. All defect descriptions were standardized into a unified taxonomy based on internal QC terminology, and duplicate entries were removed. Panels with multiple defects were retained as separate defect occurrences for Six Sigma calculations to ensure consistent and non-overlapping defect counts. Meanwhile, the field observations conducted in September to October 2025 were used solely as qualitative support for interpreting root causes and were not included in any statistical calculations. The Critical to Quality (CTQ) characteristics were singled out as per ISO 9001:2015 requirements and the company's internal standards so that the analysis would be done on the most critical attributes that are connected with customer satisfaction and product performance (Firmansyah *et al.* 2025; Jou *et al.* 2022). The analysis of data was done by combining the Six Sigma DMAIC framework with the Seven Tools of Quality. The framework made it possible to evaluate the process performance in a structured and statistically sound way. These are the DMAIC stages: Define, Measure, Analyze, Improve, and Control. Thereby, one after the other, DMAIC was used to create a visual description of the process, quantify defect levels by DPMO and Sigma calculations, determine the dominant defects *via* Pareto analysis, identify the main causes *via* fishbone diagrams, and find out the stability of the process *via* control charts (Germanova-Krasteva and Dimcheva 2020; Minh *et al.* 2024; Lubis *et al.* 2025; Pragastio et al. 2023). Each of the seven tools, including verification sheets, histograms, scatter diagrams, and flowcharts, helped promote visual and analytical clarity at each stage. The urgent need for such a structured approach arises from the fact that there is increasing pressure on plywood manufacturers to use raw material most efficiently, increase production, and meet world-class quality standards while relying increasingly on depleting natural resources.

RESULTS AND DISCUSSION

Identification of Dominant Defects

The integration of defect data from both the 2.7 mm and 9 mm meranti plywood production lines showed consistent patterns in the defects that occurred most frequently at PT Kayu Lapis Indonesia. In both datasets, the Seven Tools, especially the check sheet, histogram, and Pareto chart, were found to be useful in giving a clear identification and quantification of major defects.

Table 1. Monthly Defects in the 2.7 mm and 9 mm Production Lines (2024)

Month (2024)	Product (pcs)			Defect			Total Defects (pcs)
		Insufficient core (pcs)	Thinness (pcs)	Blistering (pcs)	Pressmark (pcs)	Brittleness (pcs)	
January	21.386	66	113	143	66	111	499
February	20.787	10	262	83	23	25	403
March	1.161	8	17	8	7	6	46
April	24.382	246	212	215	310	205	**1.188**
May	25.094	359	221	467	284	171	**1.502**
June	9.738	151	150	127	149	95	672
July	9.101	31	77	26	46	12	192
August	24.906	276	304	237	234	207	**1.258**
September	26.854	255	271	322	180	97	**1.125**
October	12.659	106	68	109	84	25	392
November	6.704	19	12	168	26	12	237
December	5.243	46	48	47	48	8	197
Total	188.015	1.573	1.755	1.952	1.457	974	7.711

Table 1 summarizes only the five CTQ defect categories applied in the DPU, DPMO, and Sigma analyses. A complete list of the 14 defect types recorded in the 2.7-mm line, including overlapping, concave core, and other non CTQ defects, is provided in Table 2. as a supplementary taxonomy. For the 2.7-mm plywood line, a total of 14 types of defects were identified.

For the 2.7-mm plywood line, a total of 14 types of defects were identified. The five most frequent types of defects were different core thickness, overlapping, concave core, brittleness, and blistering. Of these, different core thickness was observed to constitute 25.9% of the total defective number of pieces (454 pcs) as the most critical class of defect.

Table 2. Complete Defect Taxonomy for the 2.7-mm Production Line

Defect Type	Description (optional)
1. Insufficient core	Core layer missing or too thin
2. Thinness	Panel thickness below specification
3. Blistering	Surface bubbles due to poor bonding
4. Press marks	Impressions caused by press plates
5. Brittleness	Panel cracks easily under stress
6. Overlapping	Core veneers overlap beyond tolerance
7. Concave core	Core layer forms a concave shape
8. Core voids	Gaps or holes inside the core layer
9. Delamination	Separation between veneer layers
10. Glue spots	Excess adhesive visible on surface
11. Rough surface	Surface not smooth after sanding
12. Edge damage	Broken or chipped panel edges
13. Misalignment	Veneer layers not properly aligned
14. Foreign material	Contaminants embedded in the panel

To reconcile the defect taxonomy used in this study, it is important to note that Table 1 presents only the five CTQ defect categories that were used for the Six Sigma calculations (insufficient core, thinness, blistering, press marks, and brittleness). However, the 2.7 mm production line records contained a broader list of fourteen defect types, including overlapping and concave core, which were identified during the initial screening but were subsequently grouped into the five CTQ categories for analytical consistency. The percentages and totals reported in the text refer to the full fourteen defect dataset, whereas Table 1 summarizes only the CTQ level categories used for DPU, DPMO, and Sigma calculations. This distinction helps to ensure consistency between the table and the narrative. The five most frequent types of defects were different core thickness, overlapping, concave core, brittleness, and blistering. Of these, different core thickness was observed to constitute 25.9% of the total defective number of pieces (454 pcs) as the most critical class of defect.

Table 3. Defect Distribution for the 2.7-mm Production Line (2024)

Defect Type	Defect Count (pcs)	Percentage (%)
Different core thickness	454	25.9
Overlapping	312	17.8
Concave core	241	13.7
Core voids	198	11.3
Delamination	165	9.4
Other defect types (9 categories)	384	21.9
Total defects	**1,754**	**100**

The percentage value (25.9%) corresponds to 454 defect occurrences out of a total of 1,754 recorded defects in the 2.7 mm production line during 2024. Table 3 summarizes the defect distribution used for the Pareto analysis, providing the denominator and defect counts that form the basis of this calculation.

Figure 1 provides an overview of the major unit operations in the plywood production line, serving as the basis for process mapping within the DMAIC framework.

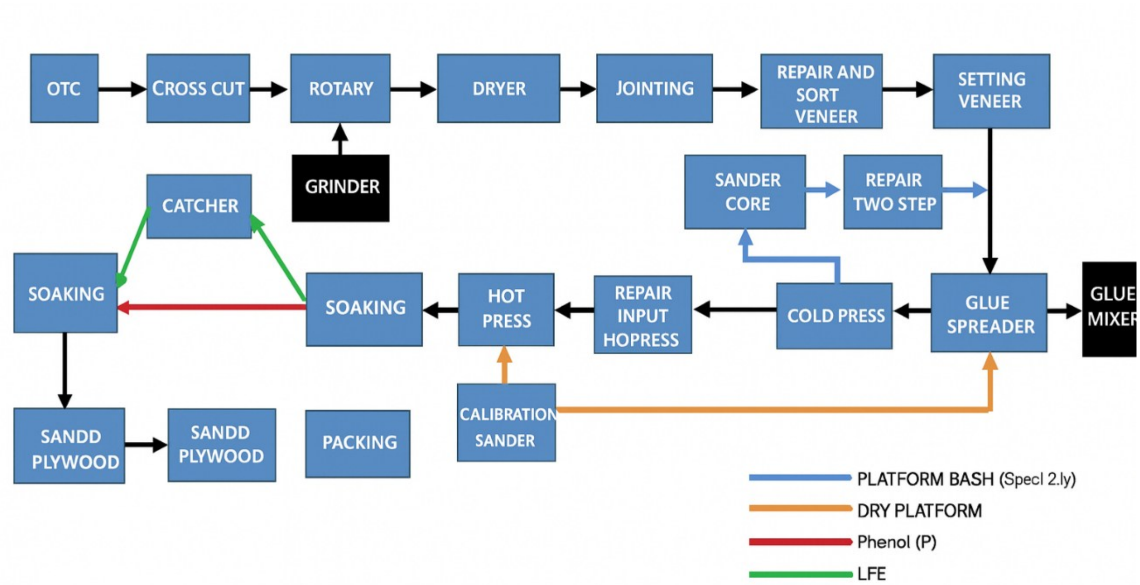

Fig. 1. Flowchart of the Indonesian plywood manufacturing work unit

Correspondingly, Pareto analysis of the types of defects found in the 9 mm plywood line showed that the first five most common types of defects comprised blistering (25%), different core thickness (23%), insufficient core (20%), press marks (19%), and brittleness (13%). These results align with the 'vital few' principles, where a small number of defect categories contribute disproportionately to overall quality losses (Juran and De Feo 2010). In this case, blistering, different core thickness, and insufficient core together accounted for 68% of all recorded defects, indicating that these categories should be prioritized for quality improvement. These recurring defects across both product lines were likely associated with process factors such as adhesive performance, core treatment, and thickness variation, as suggested by field observations and variability noted in production logs (Flores *et al.* 2025). These consistent patterns indicate that the defects are not random but stem from underlying process conditions requiring systematic corrective actions. The findings also align with previous studies that used statistical techniques to identify priority areas for improving process quality in wood composite manufacturing (Makkarennu *et al.* 2019; Vashishtha 2024).

Performance Measurement

Performance analysis was accomplished through the application of the measurement phase of the Six Sigma methodology of DMAIC. Metrics for determining the key performance indicators involved Defects Per Unit (DPU), Defects Per Million Opportunities (DPMO), or Sigma Level, through the use of Control Charts.

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To ensure transparency in the Six Sigma calculations, this study defines the defect 'opportunities' per unit as the number of CTQ characteristics inspected on each plywood panel. For both the 2.7 mm and 9 mm lines, five CTQ opportunities were evaluated per panel: insufficient core, thinness, blistering, press marks, and brittleness. Defects Per Unit (DPU) was calculated as the total number of defects divided by the total number of panels inspected. Defects Per Million Opportunities (DPMO) was computed using the standard formula:

$$\text{DPU} = \frac{\text{Total Defects}}{\text{Total Units}}$$

$$\text{DPMO} = \frac{\text{Total Defects}}{\text{Total Units} \times \text{Opportunities per Unit}} \times 1{,}000{,}000$$

For example, using the 2.7 mm line data (7,711 defects across 188,015 panels with 5 opportunities per panel):

$$\text{DPU} = \frac{7{,}711}{188{,}015} = 0.0410$$

$$\text{DPMO} = \frac{7{,}711}{188{,}015 \times 5} \times 1{,}000{,}000 = 8{,}207.6$$

Sigma levels were derived using the standard Six Sigma conversion table with the conventional 1.5σ shift applied. Accordingly, a DPMO of 59,860 corresponds to a short-term Sigma level of approximately 3.1. These formulas and the worked example have been added to improve methodological clarity.

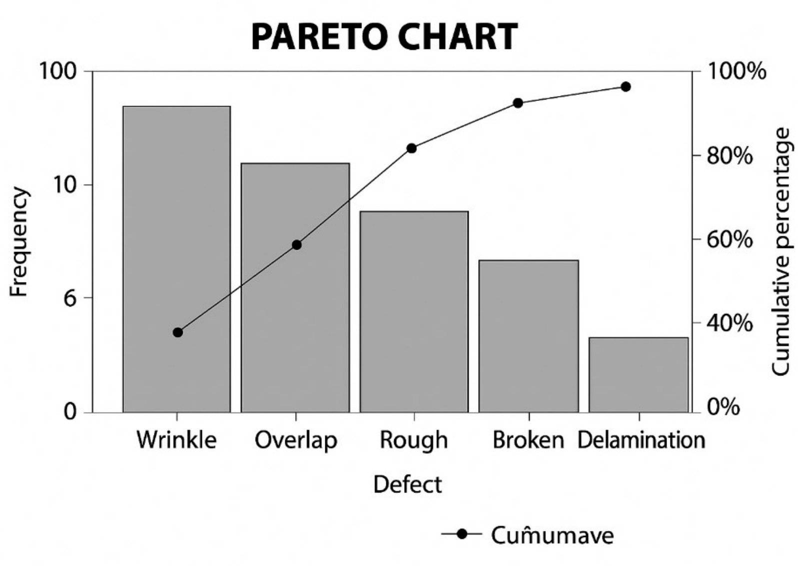

Fig. 2. Pareto diagram of the frequency distribution of defects

Figure 2 presents the Pareto Diagram for defect frequencies, while the scatter plot showing the correlation between production output and defect counts (r = +0.848) is shown as Fig. 3. The P-charts, which are used to find stable processes and spots that are out of control, are Figs. 4 and 5. They show subgroup sizes, control limits (UCL, CL, LCL), and sample information.

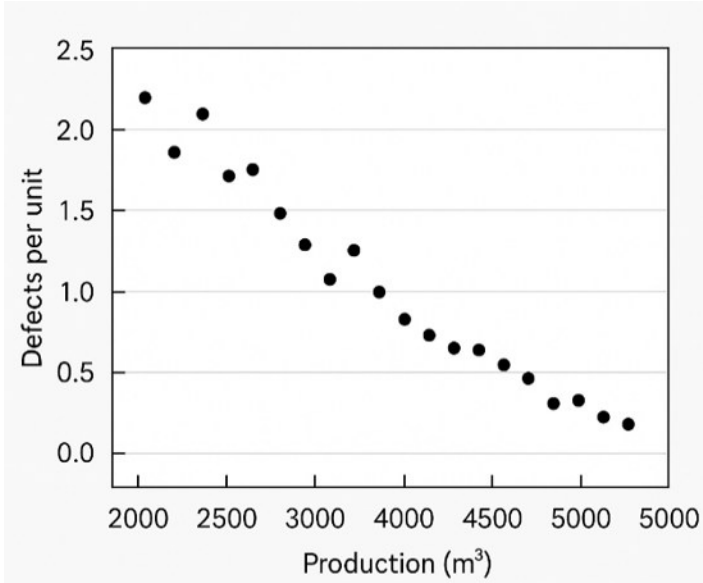

Fig. 3. Scatter Diagram for production volume vs defect rate

For the 2.7 mm plywood products, the mean DPMO was estimated approximately 59,900, corresponding to a Sigma level of 3.1. While this performance is relatively good compared with typical Indonesian wood processing operations, it remains far from the Six Sigma benchmark. Six Sigma performance corresponds to approximately 3.4 DPMO under the conventional 1.5σ shift, indicating that the current level still presents substantial room for improvement. A total of 17 subgroups were found to exceed the upper control limit in the 2.7 mm line, confirming that the process was not in statistical control. Figure 4 presents the corresponding P chart, complete with subgroup size (daily batches of 250 panels), control limits (UCL, CL, LCL), and sampling details used in the analysis.

In the case of the 9 mm plywood products, the P chart pointed to two points at which the process had fallen outside the bounds of statistical control and could be related to very high and low levels of output. These points would indicate that output variability is a function of the direct variation in the intensity of production (Makin 2025).

Although these deviations initially appeared to coincide with periods of higher and lower production intensity, attributing them solely to output volume would be speculative without supporting evidence. The scatter plot presented in Fig. 3 illustrates the relationship between production output (m^3) and defect counts per batch, based on N=24 production subgroups. The correlation coefficient was $r=+0.848$, and the relationship was statistically significant ($p<0.01$), indicating a strong positive association between output volume and defect occurrence. However, this correlation does not establish causality, and other factors, such as veneer moisture variation, glue spread inconsistency, press temperature fluctuations, or operator related differences, may also contribute to these out-of-control points. Therefore, these deviations are interpreted as potential assignable causes requiring further investigation rather than being attributed exclusively to production intensity.

Next, a scatter diagram (Fig. 3) showed that a positive correlation existed between output and defect counts with a correlation coefficient of $r = +0.848$, suggesting that an approximately proportional relationship existed between output and defects in a manner that has long been described by the 'speed-induced' effects of mass production on quality (Pyzde and Keller 2014). These points collectively indicate a need for tighter process control, particularly in light of current demand areas in very large output. Despite current process performance indicating that PT KLI meets industry standards, there remains a significant need to reduce process variation and improve Sigma Levels to compete effectively on a global quality platform (Bhuiyan and Baghel 2005). The integrated approach applied in this study provided a structured diagnosis of the production system by combining defect taxonomy, statistical process control, and root-cause analysis (Utama *et al*. 2024). To strengthen long term process control, several measurable control metrics are proposed as part of the control phase. Key process parameters that directly influence defect formation, such as glue spread weight (g/m²), press temperature (°C), and veneer moisture content (%), should be monitored routinely using control charts. In addition, a defect rate P chart should be maintained for each product line to track ongoing stability and detect emerging assignable causes. These indicators can serve as the core KPIs in a formal control plan, enabling supervisors to identify deviations early and implement corrective actions before defects escalate.

To operationalize these recommendations, a measurable control plan was developed to specify the CTQ characteristics, monitoring methods, sampling frequency, chart types, and responsible personnel. This structured plan ensures that improvements can be sustained and deviations can be detected early. The control plan is summarized in Table 4.

Table 4. Vertical Control Plan for CTQ Characteristics

	Glue Spread	Press Temperature	Veneer Moisture Content	Defect Rate (per batch)
Target Specification:	200 ± 10 g/m²	110°C ± 5°C	12% ± 2%	<4% defective panels per batch
Measurement Method	Scale measurement	Digital temperature sensor log	Moisture meter	QC inspection
Sampling Frequency	Every 30 minutes	Continuous monitoring	Every batch	Daily
Chart Type	X̄–R chart	I–MR chart	Moisture histogram / capability check	P-chart
KPI Target	Standard deviation < 15 g/m²	95% of readings within control limits	<10% sheets out of specification	Zero UCL violations
PIC	QC Technician	Press Supervisor	Dryer Operator	QC Engineer
Reaction Plan	Adjust glue spreader settings and recheck three consecutive samples.	Stop press, recalibrate temperature controls, verify stability before restarting.	Re-dry out-of-spec sheets and adjust dryer temperature/ humidity settings.	Conduct root-cause review, implement corrective action, and verify next batch stability.

To assess process stability, P charts were constructed for both the 2.7-mm and 9-mm production lines. These charts visualize the proportion of defective panels across subgroups and help identify any out-of-control conditions. Figures 4 and 5 present the P charts for each line, respectively.

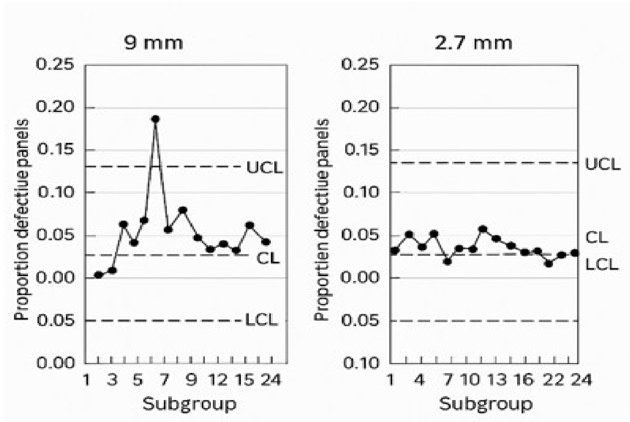

Fig. 4. P-chart for process stability in the 9 mm and 2.7 mm lines

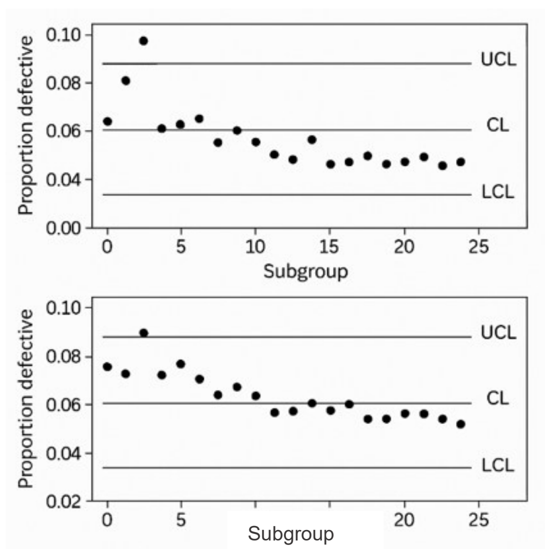

Fig. 5. P-chart for 2.7 mm production line defects

The chart displays the proportion of defective panels across 25 subgroups, with control limits (UCL, CL, LCL), indicating process stability. Several points exceed the upper control limit, suggesting potential out-of-control conditions requiring investigation.

This chart shows the defect proportion per subgroup in the 9-mm line. Most data points fell within control limits, although a few exceeded the UCL, indicating possible process variation or instability.

Root Cause Analysis

Using the Analyze phase of the DMAIC framework, the root causes were grouped into five major categories: Man, Machine, Method, Material, and Environment. This classification helped structure the causal analysis and ensured that contributing factors were examined systematically rather than individually (Fig. 6).

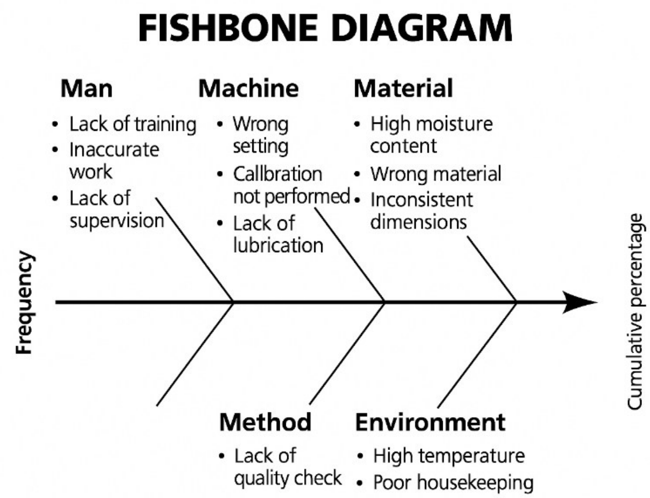

Fig. 6. Fishbone diagram of critical defect points

To enhance clarity and strengthen the practical interpretation of the Fishbone Diagram, the dominant defects were explicitly mapped to their supporting evidence, root causes, and recommended countermeasures. This Defect–Cause–Action matrix summarizes the key analytical findings and provides a direct link between observed quality issues and actionable improvements.

Table 5. Defect–Cause–Action Matrix

Defect Type	Evidence (2024 Data)	Root Cause Category	Proposed Countermeasure
Insufficient core	22% veneer moisture > 12% ± 2%; core gaps in 198 pcs	Material / Methods	Moisture screening; improved lay-up SOP; hourly CCP checks
Thinness	14% panels outside ±0.10 mm tolerance	Machine	Sander calibration every shift; gauge verification
Blistering	Press temp variation 102–118°C; glue spread SD 22.4 g/m²	Machine / Material	Hot-press control chart; glue spread monitoring
Press marks	Dust >150 µg/m³; poor housekeeping	Environment	5S audits; press-area cleaning schedule
Brittleness	Operator fatigue; inconsistent glue spread	Man / Machine	Training frequency ↑; glue spread SOP reinforcement

Human factor

Human related factors emerged as major contributors to several key defects, particularly thinness, press marks, and insufficient core, consistent with the standardized defect taxonomy used in this study. Plant level evidence supports this finding: internal SOP audits conducted in 2024 recorded a compliance rate of only 78%, with the most frequent deviations occurring in glue spread application and veneer placement procedures. Operator training records further showed that refresher training was conducted only once every six months, while staffing logs indicated that the 2.7-mm line frequently operated with reduced personnel during peak demand periods, conditions that increase the likelihood of operator fatigue and lapses in concentration. These observations align with previous research emphasizing the importance of operator skill, adequate training frequency, and strict procedural adherence in maintaining product quality in high precision manufacturing environments (Minh *et al.* 2024; Utama *et al.* 2024). Overall, the findings highlight that addressing the 'Man' element of the Ishikawa framework is as critical as mechanical calibration in achieving process stability (Firmansyah *et al.* 2025).

Machine factors

Machine-induced variability was identified as a significant contributor to several critical to quality defects, particularly blistering, brittleness, and core thickness variation. Plant level data support this finding: hot press temperature logs from 2024 showed fluctuations ranging from 102 to 118 °C (mean 111.2°C, SD 4.7°C), exceeding the recommended operating window of 110°C ± 5°C and increasing the likelihood of incomplete adhesive curing (Ding *et al.* 2022; Ross 2010). Glue spread measurements also exhibited substantial variability, with weights ranging from 180 to 245 g/m² (SD 22.4 g/m²), as recorded in the calibration sheets for the glue spreader. In addition, sanding line measurements indicated that 14% of sampled panels fell outside the specified thickness tolerance of ±0.10 mm, based on caliper readings taken every 30 minutes during production. Misalignment in the core builder, documented in two quarterly calibration reports, further contributed to uneven veneer joints and inconsistent bonding (Stark 2010). These findings collectively demonstrate that more rigorous and frequent calibration procedures are required across the manufacturing line, as equipment related deviations directly impair adhesive performance, veneer bonding, and the dimensional accuracy of the finished panels (Bowyer *et al.* 2002).

Method factors

Several process-related deficiencies were also identified as contributors to quality variation, complementing the mechanical issues described earlier. SOP audit records from 2024 showed a compliance rate of 81%, with the most frequent deviations occurring at two critical control points where inspections were either delayed or omitted. In addition, inspection logs indicated that checks at these points were conducted only once every two hours, rather than at the recommended hourly interval, reducing the likelihood of detecting process drift in real time. The absence of a structured and systematic method for fault identification further limited the consistency of corrective actions across shifts. These process short comings particularly inconsistent SOP adherence, insufficient inspection frequency, and weak documentation practices, align with previous findings that emphasize the importance of robust process discipline in maintaining quality performance (Oakland 2014; Uddin 2021; Vashishtha 2024). Rather than implying ineffectiveness of the DMAIC Control phase, the results suggest that the existing control mechanisms were not fully implemented on the shop floor, underscoring the need for stronger procedural compliance and more frequent monitoring (Anwar *et al.* 2015).

Material factors

Material related factors, particularly veneer quality, were also identified as major contributors to defects such as insufficient core and depressed core. Moisture content measurements taken during the 2024 production period showed substantial variability, ranging from 9.8% to 18.6% (mean 13.4%, SD 2.7%), with 22% of sampled sheets exceeding the plant's QC acceptance limit of 12% ± 2%. Veneer sheets with moisture levels above this threshold were frequently associated with poor adhesive penetration and weak bonding during hot pressing, consistent with findings by Frihart *et al.* (2021). Dimensional variability in core sheets further contributed to bonding failures, with width deviations of up to ±3.2 mm relative to the nominal specification, as recorded in the veneer grading logs. In several instances, foreign material contamination was also documented at the lay-up station, increasing the likelihood of surface irregularities and localized bond disruption (Malau *et al.* 2022; Susanti 2023). These plant-specific observations underscore the need for tighter quality control at the front end of the process, particularly through improved veneer conditioning, stricter moisture content screening, and enhanced storage practices to minimize moisture related degradation prior to lay up (Teischinger and Müller, 2012).

Environment factors

Although secondary compared with mechanical and material influences, environmental factors still contributed to the occurrence of defects such as press marks and blistering. Environmental audit records from 2024 documented elevated airborne dust levels around the hot-press area, with particulate counts exceeding the plant's housekeeping threshold of 150 µg/m³ during three weekly inspections. Such dust accumulation can interfere with veneer surface cleanliness and reduce bond integrity, consistent with findings by Li *et al.* (2020). Lighting assessments at two critical inspection stations also showed illumination levels of 210 of 240 lux, below the recommended 300 lux standard for surface-defect detection, increasing the likelihood that minor veneer irregularities escaped operator inspection. These observations highlight the importance of improved workplace organization and stricter environmental discipline, particularly through consistent 5S implementation, to maintain a controlled production environment suitable for high-precision wood processing (Gozali *et al.* 2020; Firmansyah *et al.* 2025; Pragastio et al. 2023).

To strengthen the root cause interpretation, several quantitative indicators from the production records were incorporated into the analysis. Hot press temperature logs showed fluctuations between 102 and 118 °C, exceeding the recommended operating window of 110 °C ± 5 °C, which aligns with the high incidence of blistering and incomplete adhesive curing. Glue spread measurements collected during field observations also exhibited variability (ranging from 180 to 245 g/m²), supporting the link between uneven adhesive application and defects such as insufficient core bonding and press marks. In addition, veneer moisture readings taken at the dryer outlet ranged from 9 to 18%, whereas the company's internal standard specifies 10 to 12%; this variability corresponds with the occurrence of concave cores and brittleness. These quantitative indicators reinforce the causal chain between process variation and defect formation, and they directly inform the countermeasures proposed in the Improve–Control recommendations.

Integrated Interpretation and Practical Implications

Integrating the DMAIC framework with the Seven Quality Tools provides an effective data-based diagnostic method for plywood production. The Six Sigma approach not only guarantees a structured and repeatable improvement cycle but also makes it more manageable to move from problem identification to sustained process control. Meanwhile, the Seven Quality Tools provide detailed, data-based insights that help decipher complex defect patterns (Pyzde and Keller 2014). The results for both product lines show that the quality of adhesive application, veneer preparation, and thickness cutting are the main weak areas. The current sigma levels may be at the same level as the regional industry average, but the constant variation in the process still indicates that there is a lot of room for improvement. The root cause analysis traces the defects back to several contributing factors, the most important being the human factor, the machine not being consistent, and the working methods not being defined (Antony 2003).

These discoveries, from a practical viewpoint, highlight a tactical demand for PT Kayu Lapis Indonesia to invest in first machine calibration and then operator competence assuring as their main interventions. To be more precise, the coming into force of the standardized operating procedures (SOPs) for glue weight application and hot press temperature monitoring—110 °C +- 5 °C being the operating temperature—has no alternative if blistering and brittleness are to be minimized (Ebnesajjad and Landrock 2015; Sutiawan *et al.* 2020). The plus of having an automated sander calibration schedule is less thickness deviation. This, in turn, creates more efficiency in raw material use leading to less waste. Through the establishment of a continuous improvement culture, the company can navigate around these core areas and at the same time reap the benefits of cost-efficient production and strengthening its competitive advantage in the high-standard global export market (Pragastio et al. 2023).

Table 6. Improve–Control Action Plan

Defect / Issue	**Action / Countermeasure**	**PIC / Owner**
Blistering, Brittleness	- Standardize hot-press temp at 110°C ± 5°C - Press-parameter checklist	Production Supervisor QC Engineer
Thickness Variation	- Weekly sander calibration - Monthly gauge verification	Maintenance Team QC Technician
Insufficient Core, Core Voids	- Standardize glue spread SOP - Operator retraining	Production Supervisor; Training Coordinator
Press Marks	- Improve housekeeping around hot-press area - Weekly 5S audits	Line Leader 5S Committee
Concave Core, Moisture Defect	- Tighten veneer moisture control - Improve storage conditions	Drier Operator QC Staff
Human error, SOP Noncompliance	- SOP refresher training - Visual work instructions	HR / Training Unit, Line Leader
Frequency	**Control Metric**	**Expected Impact**
- Per shift - Weekly / monthly - Daily SOP checks - Quarterly training - Weekly 5S audit	- Hot-press temp chart - Thickness deviation chart - Glue spread weight (g/m²) - Moisture distribution chart - Defect rate P-chart	- Reduced blistering - More stable curing - Lower variation - Higher consistency - Improved Sigma

Improve – Control Action Plan

To translate the diagnostic findings into actionable improvements, a structured Improve – Control plan was developed to guide implementation at PT Kayu Lapis

Indonesia. This plan links each dominant defect to a specific corrective action, responsible personnel, monitoring frequency, control metrics, and expected impact. By organizing the improvement strategy in this way, the company can systematically address the root causes identified in the DMA phases and establish measurable indicators for sustaining long term process stability. The action plan is summarized in Table 6.

CONCLUSION

This report verified that the integration of the Six Sigma DMAIC method and the Seven Quality Tools is an effective and systematic approach to improving the quality of plywood manufacturing processes at PT Kayu Lapis Indonesia. By examining the meranti plywood production lines for 2.7 mm and 9 mm products, the five major defect categories, blistering, thinness, insufficient core, press marks, and brittleness, were identified as the dominant contributors to production losses. The calculated Sigma level of 3.1 indicated that the process demonstrated moderate capability but remained highly sensitive to fluctuations in machine settings, material conditions, and operator performance.

In response to these system-level issues, several targeted improvement actions are recommended. Enhanced hot-press calibration is expected to reduce blistering defects by at least 20%, while improved sander alignment and gauge verification aim to achieve a 15% reduction in thinness defects. Increasing operator training frequency and reinforcing SOP compliance are projected to lower press-mark and brittleness defects by reducing human-factor deviations. These improvements should be monitored through updated P-charts and KPI dashboards to verify measurable reductions in defect rates over time. Complementary initiatives, such as adopting standardized SOPs for glue-spread and press-temperature control, implementing preventive maintenance for sanding and core-building equipment, and strengthening 5S housekeeping practices, will further support long-term process stability. To ensure sustainment, monthly 5S audits should be implemented and the results incorporated into the Control-phase dashboard for routine supervisory review. A limitation is that improvement actions were not implemented during the study; future work will validate reductions *via* post-implementation QC metrics.

Declaration of Competing Interest

To the authors' knowledge, there are no conflicts of interest or factors from personal relationships or affiliations that could have influenced this work.

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REFERENCES CITED

Antony, J. (2003). *Design of Experiments for Engineers and Scientists*, pp. 1-152.

Anwar, C., Purwanto, A., Zaenal Abidin, R., Febry Prabowo, R., Puspita Rani, C., Fahmi, K., and Budi Sulistyo, A. (2015). "Which are the most affected manufacturing performance?" in: *AND ISO* (Vol. 9001).

Bhuiyan, N., and Baghel, A. (2005). "An overview of continuous improvement: From the past to the present," *Management Decision* 43, 761-771. https://doi.org/10.1108/00251740510597761

Bowyer, J. L., Shmulsky, R., and Haygreen, J. G. (2002). *Forest Products and Wood Science: An Introduction*, Issue Ed. 4, Iowa State Press.

Cordier, M., Johannsen, N., Kietz, B., Berthold, D., and Mai, C. (2025). "Plywood manufacturing using various combinations of hardwood species," *Forests* 16(4), article 622. https://doi.org/10.3390/f16040622

Dahlia, A., Tongsuku, L. O. A. S., and Gunawan, S. (2024). "Quality control analysis to minimize the risk of defective products using statistical process control (SPC) and failure modes and effect analysis (FMEA) methods (Case Study: PT XYZ Samarinda)," *IJIEM - Indonesian Journal of Industrial Engineering and Management*. https://doi.org/10.22441/ijiem.v5i2.24039

Ding, Y., Pang, Z., Lan, K., Yao, Y., Panzarasa, G., Xu, L., Lo Ricco, M., Rammer, D., Zhu, J., Hu, M., Pan, X., Li, T., Burgert, I., and Hu, L. (2022). "Emerging engineered wood for building applications," *Chemical Reviews* 123(5), article 2c00450. https://doi.org/10.1021/acs.chemrev.2c00450

Ebnesajjad, S., and Landrock, A. H. (2015). "Chapter 4 - Classification of adhesives and compounds," in: *Adhesives Technology Handbook*, Third Ed., S. Ebnesajjad and A. H. Landrock (eds.), William Andrew Publishing, pp. 67-83. https://doi.org/https://doi.org/10.1016/B978-0-323-35595-7.00004-8

Firmansyah, Priyanto, A., Hakim, P. R., Sulaeman, D., Prasetyo, Y., and Prastyo, Y. (2025). "Quality control analysis of defective products on prism sheets using lean six sigma with the DMAIC concept," *International Journal of Research and Innovation in Social Science* 2025, article 9010181. https://doi.org/10.47772/ijriss.2025.9010181

Flores, M. X. L., Rogríguez, B. S. M., César, P., and Jijón, E. O. P. (2025). "Quality optimization in footwear production: A variability study using Six Sigma methodology," *Revista Minerva* 6(16), article 186. https://doi.org/10.47460/minerva.v6i16.186

Frihart, Charles R, Hunt, and Christopher G. (2021). *Wood Adhesives: Bond Formation and Performance*. Centennial Ed., General Technical Report FPL-GTR-190, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, pp. 10.1-10.24.

Germanova-Krasteva, D., and Dimcheva, I. (2020). "Analysis of defects and their impact on the production losses using Pareto diagrams," E3S Web of Conferences 207, article 03007. https://doi.org/10.1051/e3sconf/202020703007

Gozali, L., Sagitta, J. N., and Ahmad. (2020). "Quality control to minimize defective products in the outer part production process," in: *Proceedings of the Tarumanagara International Conference on the Applications of Social Sciences and Humanities (TICASH 2019)*," pp. 71-75. https://doi.org/10.2991/assehr.k.200515.013

Hildebrandt, J., Hagemann, N., amd Thrän, D. (2017). "The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe," *Sustainable Cities and Society* 34, 405-418. https://doi.org/10.1016/j.scs.2017.06.01 3
Jou, Y., Silitonga, R., Lin, M.-C., Sukwadi, R., and Rivaldo, J. (2022). "Application of six sigma methodology in an automotive manufacturing company: A case study," *Sustainability* 14(21), article 14497. https://doi.org/10.3390/su142114497
Juran, J. M., and De Feo, J. A. (2010). *Juran's Quality Handbook: The Complete Guide to Performance Excellence*, 6th Ed., McGraw Hill. http://accessengineeringlibrary.com/browse/jurans-quality-handbook-the-complete-guide-to-performance-excellence-sixth-edition
Koh, J., and Singgih, M. (2021). "Implementation lean manufacturing method of plywood manufacture company," *Journal Industrial Services* 8(2), article 9022. https://doi.org/10.12962/j23546026.y2020i2.9022
Li, W., Zhang, Z., Zhou, G., Leng, W., and Mei, C. (2020). "Understanding the interaction between bonding strength and strain distribution of plywood," *International Journal of Adhesion and Adhesives* 98, article 102506. https://doi.org/https://doi.org/10.1016/j.ijadhadh.2019.102506
Lubis, M. C., Simanjuntak, F. A., and Payana, S. D. (2025). "Analisis Menggunakan Peta Kendali I-MR dan Diagram Pareto pada Produksi Kayu Lapis di PT. SLJ Global Tbk, Samarinda," *AKSIOMA: Jurnal Sains Ekonomi Dan Edukasi* 2(6), article 1340. https://doi.org/10.62335/aksioma.v2i6.1340
Makin, J. G. (2025). *An Introduction to Modern Statistical Learning*. http://arxiv.org/abs/2207.10185. https://doi.org/10.48550/arXiv.2207.10185
Makkarennu, Natsir, H., and Supratman. (2019). "Supply chain management of the plywood industry in Indonesia," in: *IOP Conference Series: Materials Science and Engineering*, 593. https://doi.org/10.1088/1757-899x/593/1/012008
Malau, L., Anjani, R., Ulya, N., and Martin, E. (2022). "Competitiveness and determinants of Indonesian plywood export," *Jurnal Sylva Lestari* 10(2), article 580. https://doi.org/10.23960/jsl.v10i2.580
Minh, H. C., Le, M.-T., Khang, H., Lu, K., Hang, T., and Nguyen. (2024). "Continuous improvement of productivity and quality with applying lean six sigma: A case study," *Journal of Technical Education Science* 19(3), article 1586. https://doi.org/10.54644/jte.2024.1586
Müller, D., Szemkus, N., and Hiete, M. (2023). "Carbon balance of plywood from a social reforestation program in Indonesia," *Scientific Reports* 13, article 13552. https://doi.org/10.1038/s41598-023-40580-0
Oakland, J. (2014). *Total Quality Management and Operational Excellence: Text with Cases*. https://doi.org/10.4324/9781315815725
Pragastio, G. A., Garside, A. K., and Saputro, T. E. (2023). "Six Sigma approach with integration of FMEA–Fuzzy SWARA–Fuzzy WASPAS to minimize bottled water defects," *Jurnal Ilmiah Teknik Industri* 22(1), 113–123. https://doi.org/10.23917/jiti.v22i1.21370
Puruwita, I., and Oktora, S. I. (2019). "Exports and competitiveness of Indonesian plywood," in: *Proceedings of the International Conference on Trade 2019 (ICOT 2019)*. https://doi.org/10.2991/icot-19.2019.23
Pyzde, T., and Keller, P. A. (2014). *The Six Sigma Handbook*, 4th Ed., McGraw Hill Professional.

Ramos-Maldonado, M., Gutiérrez, F., Gallardo-Venegas, R., Bustos-Avila, C., Contreras, E., and Lagos, L. (2025). "Machine learning and industrial data for veneer quality optimization in plywood manufacturing," *Processes* 13(4), article 1229. https://doi.org/10.3390/pr13041229

Romdloni, M. S., & Nuruddin, M. (2025). Quality Control of Wood Pallet at CV. Mandiri Jaya to Reduce Product Defects Using Statistical Quality Tools and FMEA Methods. *G-Tech: Jurnal Teknologi Terapan 9*(2), 748–757. https://doi.org/10.70609/gtech.v9i2.6616

Ross, R. J. (ed.) (2010). *Wood Handbook: Wood as an Engineering Material*, General Technical Report FPL-GTR-190, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 509 p.

Stark, N. M. (2010). "Wood-based composite materials: Panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials," in: *Wood Handbook: Wood as an Engineering Material*, Centennial Ed., General Technical Report FPL-GTR-190, R. J. Ross (ed.), U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, pp. 11.1-11.28.

Supriadi, A., Trisatya, D. R., and Sulastiningsih, I. (2020). "Sifat Kayu Lapis yang Dibuat dari Lima Jenis Kayu Asal Riau," *Jurnal Ilmu Pertanian Indonesia* 25, 657-663. https://doi.org/10.18343/jipi.25.4.657

Susanti, H. D. (2023). "Risk prevention of plywood product defects using Failure Mode Effect Analysis (FMEA) in the Indonesian plywood processing industry," *Wood Material Science & Engineering* 18, 2049-2059. https://doi.org/10.1080/17480272.2023.2214527

Sutiawan, J., Nurhanifah, Anggiriani, S., Hermawan, D., Massijaya, M., Sulastiningsih, I., and Abdillah, I. (2020). "Physical mechanical properties of plywood made from lesser-known wood veneers bonded with phenol formaldehyde adhesive," in: *IOP Conference Series: Materials Science and Engineering*, 935, article 12055. https://doi.org/10.1088/1757-899x/935/1/012055

Teischinger, A., and Müller, U. (2012). "Wood and natural fibre-based light weight panels: Opportunities and limitation," *in: 8th European Wood-based Panel Symposium*, Hannover, October 11-12, 2012.

Uddin, M. (2021). "Improving product quality and production yield in wood flooring manufacturing using basic quality tools," *Int. J. Qual. Res.* 15, 155-170. https://doi.org/10.24874/ijqr15.01-09

Utama, D. M., Abdullah, F. F., Amallynda, I., and Baroto, T. (2024). "Integrated production-inventory model for multi-item raw materials with exponential quality degradation: a real case study," *OPSEARCH* 61, 1862–1887. https://doi.org/10.1007/s12597-024-00759-z

Vashishtha, S. (2024). "Plywood proficiency: Navigating quality assurance in manufacturing," *American Journal of Construction and Building Materials* 8(2), 52-61. https://doi.org/10.11648/j.ajcbm.20240802.13

Wahyudi, I., and Sitanggang, J. (2016). "Kualitas Kayu Meranti Merah (*Shorea leprosula* Miq.) Hasil Budi Daya*," Jurnal Ilmu Pertanian Indonesia* 21, 140-145. https://doi.org/10.18343/jipi.21.2.140

Widyastutik, W., and Arianti, R. (2014). "Analisis strategi kebijakan mutu dan standar produk kayu lapis dalam rangka meningkatkan daya saing ekspor," *Jurnal Agribisnis Indonesia* 2, 75-92. https://doi.org/10.29244/jai.2014.2.1.75-92

Yi, Z., Luo, L., Lu, Q., Chen, M., Zhu, W., and Zhang, Y. (2024). "An efficient and accurate surface defect detection method for quality supervision of wood panels," *Measurement Science and Technology* 35(5), article 055209. https://doi.org/10.1088/1361-6501/ad26c9

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