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# Temporal Analysis of Material Retention and Loss at Final Inspection Stage in Plywood Manufacturing

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## Abstract

Despite extensive studies on product quality and process optimization in plywood manufacturing, limited attention has been given to interpreting routine inspection data as indicators of temporal material retention efficiency. Efficient utilization of forest resources is not only determined by harvesting practices but also by the ability of downstream industries to retain wood material within productive manufacturing flows. In plywood manufacturing, the proportion of material classified as acceptable product represents the primary yield of forest-derived raw material. This study analyzes the temporal dynamics of primary yield in plywood manufacturing using monthly production inspection data. A quantitative descriptive approach was applied to data collected over a four-month period, where overlap-related (OVL) products were classified as acceptable output, while under-thickness deviations (UTY) were treated as material loss. The results show that overlap-related products accounted for more than 94% of the total inspected volume, indicating a consistently high primary yield. Minor fluctuations in yield across months suggest temporal variability in material retention efficiency. The findings demonstrate that high primary yield contributes positively to forest resource utilization efficiency by reducing the need for additional raw wood input and supporting sustainable forest resource management.



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## INTRODUCTION

Manufacturing efficiency in wood-based industries is strongly influenced by the ability of production systems to retain wood material within acceptable product specifications (Hosseini & Peer, 2022). In plywood manufacturing, veneer-based panels undergo multiple processing stages before being evaluated at the final inspection stage, where products are classified according to dimensional and quality standards. According to Borkowski and Knop (2016), in production practice, this inspection is typically categorized as an acceptance inspection, and its main purpose is to eliminate from the manufacturing process the products (materials, semi-finished products, parts) that do not meet the requirements. However, from a material utilization perspective, inspection results also represent the final distribution of wood material between retained output that remains within the productive flow and downgraded output that exits the acceptable product stream (Vashishtha, 2024).

The ability of a manufacturing system to maintain a high proportion of retained material is a critical indicator of production efficiency (Ongbali et al., 2021). Awaliyah et al. (2016) reported that variations in raw material characteristics, processing parameters, machine calibration, and operational control can influence the proportion of panels that meet product specifications. These variations may not only affect product quality and performance but also reflect changes in material utilization efficiency at the manufacturing level. Despite the routine availability of inspection data in industrial plywood production, such data are commonly used for short-term quality monitoring rather than for evaluating material retention stability over time.

Previous studies in plywood manufacturing have largely focused on defect characterization (Ge et al., 2023; Urbonas et al., 2019), veneer properties and bonding performance (Bekhta & Salca, 2018; Liu et al., 2018), process/adhesive optimization for improved panel performance (Dukarska et al., 2022; Sutiawan et al., 2024), and quality control performance and consistency (Chen et al., 2022; Dahlia et al., 2024). These studies have provided substantial insights into the technical factors influencing panel quality, bonding integrity, and defect occurrence within plywood production systems. Consequently, most previous research has primarily emphasized product quality and technical performance as the main analytical focus in plywood manufacturing processes.

However, relatively limited attention has been given to the interpretation of inspection-based production data as indicators of material flow efficiency within manufacturing systems. In particular, the temporal variability between retained and downgraded products has rarely been evaluated as a dynamic indicator of material utilization stability during production. This limitation represents an important analytical gap, since fluctuations in retained proportions may reflect underlying instability in production performance and material handling efficiency.

This indicates a clear research gap, as the dynamic relationship between retained and downgraded material remains insufficiently understood, despite its direct relevance to evaluating manufacturing efficiency and resource utilization. Without incorporating a temporal and material flow–oriented perspective, inspection data cannot adequately reflect the stability of production performance or reveal short-term inefficiencies that may accumulate into significant material losses at an industrial scale.

Viewing inspection outcomes through a material flow perspective allows production data to be reinterpreted beyond conventional quality metrics (Eben-chaime, 2021). Within this perspective, the total inspected volume represents system input at the final inspection boundary, retained products represent effective material utilization, and downgraded products represent material loss from the acceptable production flow. Expressing retained and lost proportions relative to total inspected volume enables normalization across different production periods and provides a basis for evaluating efficiency stability over time (Bacsi, 2019; Borysiuk et al., 2013; Pramreiter et al., 2023).

Evaluating temporal patterns of retained and downgraded output is particularly important in plywood manufacturing systems, where production conditions may vary across operational periods. Even relatively small changes in material loss may accumulate into significant material implications when scaled to industrial production volumes (Allwood et al., 2013; Pramreiter et al., 2023). Therefore, a temporal analytical framework is required to capture fluctuations in manufacturing efficiency and to provide a more comprehensive understanding of production stability (Oliver & James, 2016).

Material Flow Analysis (MFA) provides a systematic framework for evaluating industrial efficiency by tracing material movement within defined system boundaries. Within this framework, production systems are treated as bounded material flow units where input, retained output, and material loss can be quantified using mass balance principles. Applying MFA concepts at the final inspection stage enables inspection-based data to be reinterpreted as components of material flow performance. This approach allows production inspection results to be transformed into efficiency indicators that describe retained material proportion, downgraded output proportion, and temporal stability of manufacturing performance (Magnanini et al., 2024).

Based on this perspective, the present study aims to analyze the temporal variability of retained and downgraded plywood products at the final inspection stage using inspection-based production data. The study further evaluates retained and lost material proportions as indicators of manufacturing-level material utilization efficiency and introduces derived variability and loss intensity metrics to assess the stability of production performance over time. By repositioning routine inspection data within a material flow–oriented analytical framework, this study provides an alternative approach for evaluating efficiency dynamics in plywood manufacturing systems.

## METHODS

### Research Design and Analytical Framework

This study employed a quantitative descriptive research design combined with a temporal material retention framework to evaluate manufacturing-level material utilization performance in plywood production. The analysis was conducted using routine production inspection records and focused on interpreting inspection outcomes as components of material flow within a defined system boundary. The analysis was structured using a material flow–based yield accounting approach derived from the principles of Material Flow Analysis (MFA). Within this framework, wood material was traced from system input to retained output and material loss at the final inspection stage.

Rather than treating inspection results solely as quality indicators, this study reclassified inspection outcomes into retained and downgraded material categories. Within this framework, the final inspection stage was considered a bounded material flow unit, where total inspected volume represents system input, acceptable panels represent retained output, and downgraded panels represent material loss from the main productive stream. Temporal analysis was applied to evaluate stability and variability in retained and downgraded proportions across observation periods.

### Data Source and Observation Period

The study utilized secondary production inspection data obtained from an industrial-scale plywood manufacturing facility in East Kalimantan, Indonesia. Data were collected from routine monthly inspection records over a four-month observation period. The selection of this observation window was constrained by data accessibility and the availability of consistent, quality-controlled inspection records within the same operational setting. Therefore, the dataset represents a continuous short-term production snapshot rather than a long-term time series. Given the limited number of temporal observations ($n = 4$), the analysis was intentionally designed as a descriptive and exploratory assessment of temporal variation rather than a statistically inferential time-series analysis. The objective was to identify patterns of material retention and loss within a bounded production context, rather than to generalize temporal trends beyond the observed period.

The recorded variables consisted of total inspected volume (Total Check), acceptable product volume classified as overlap-related panels (OVL), and downgraded volumes due to under-thickness deviations classified as UTY and UTY-A. All measurements were expressed in cubic meters ($m^3$) to ensure consistency in volume-based comparison and proportional analysis.

The primary research tools used in this study were spreadsheet-based data processing software for organizing inspection records and performing numerical calculations, as well as standard graphical tools for visualizing temporal trends. No specialized measuring instruments or proprietary software were employed, as the study relied on existing inspection data generated through standard industrial measurement procedures.

## System Boundary and Material Classification

The system boundary was defined at the final inspection stage of the plywood manufacturing process, where all inspected panels were evaluated and classified according to quality-based criteria. Within this boundary, overlap-related (OVL) products were classified as acceptable output that remained within the productive manufacturing flow and were therefore treated as retained material. In contrast, under-thickness deviations (UTY and UTY-A) were classified as material loss because they exited the main productive flow and did not contribute to acceptable final products. This classification provided a clear basis for distinguishing between effective material utilization and loss within the defined system boundary.

## Yield, Loss, and Derived Efficiency Indicators

Manufacturing material utilization performance was quantified using indicators derived from the material balance principle of Material Flow Analysis (MFA), where total inspected volume represents system input, acceptable products represent retained output, and under-specification products represent material loss. The total inspected volume was treated as system input, while retained and downgraded volumes represented the distribution of output within the defined boundary. The retained proportion was calculated as the ratio of acceptable product volume (OVL) to total inspected volume, expressed as a percentage. The downgraded proportion was calculated as the ratio of under-thickness deviation volume (UTY and UTY-A) to total inspected volume, also expressed as a percentage.

Although the indicators applied in this study are derived from established material balance principles, their application as retained–loss efficiency metrics at the final inspection stage represents a contextual adaptation rather than a direct adoption of previously published formulas. In addition, derived indicators were introduced to describe temporal stability and loss intensity, allowing efficiency assessment beyond absolute yield values within the defined system boundary.

Retained was defined as the proportion of overlap-related products relative to the total inspected volume, while material loss was defined as the proportion of under-thickness deviations relative to the total inspected volume. These indicators were calculated using Equations (1) and (2).

$$\text{Retained (\%)} = \frac{OVL}{Total\ check}\ x\ 100\% \tag{1}$$

$$\text{Material Loss (\%)} = \frac{UTY+UTY-A}{Total\ check}\ x\ 100\% \tag{2}$$

In addition to primary yield and material loss, two derived efficiency indicators were applied. Temporal stability of material retention efficiency was assessed using the Yield Variability Index (YVI), which expresses the relative variation in retained proportions across the observation period and is defined as a dimensionless index. The YVI was calculated using Equation (3).

$$\text{YVI} = \frac{Max\ Retained - Min\ Retained}{Mean\ Retained} \tag{3}$$

In addition, the Loss Intensity Index (LII) was calculated to express the magnitude of material loss relative to retained output, providing insight into loss intensity independent of total input volume. The LII was calculated using Equation (4) as a dimensionless ratio of material loss to retained output.

$$\text{LII} = \frac{UTY+UTY-A}{OVL} \tag{4}$$

These indicators provide a coherent framework for quantifying material retention, loss, and efficiency stability within the defined system boundary. By integrating material balance–based yield measures with derived variability and intensity indicators, the approach enables a systematic assessment of temporal efficiency dynamics in plywood manufacturing, forming the basis for the subsequent analysis of results.

## Data Analysis and Decision Rules

Data analysis was conducted using descriptive quantitative techniques. Monthly retained and lost material proportions were analyzed to identify temporal patterns and variability in material utilization efficiency. Graphical trend analysis was applied to support interpretation of changes in primary yield and material loss over time.

Decision rules for drawing conclusions were defined as follows: higher retained proportions were interpreted as indicators of higher primary yield and more efficient utilization of forest-derived raw materials; lower material loss and lower loss intensity values were interpreted as indicators of reduced inefficiency in material use; and lower variability in retained proportions over time, as reflected by the YVI, was interpreted as evidence of greater stability in forest resource utilization efficiency.

The methodological contribution of this study lies in the contextual adaptation of inspection-based production data into a material flow–oriented efficiency framework. Rather than treating inspection outcomes solely as quality performance indicators, the present approach operationalizes retained and downgraded classifications as flow components within a bounded system. By integrating temporal variability and loss intensity metrics into conventional yield accounting, the framework extends static efficiency measurement toward a dynamic evaluation of material retention stability across observation periods

## RESULTS AND DISCUSSION

### Temporal Patterns of Primary Yield

The inspection results indicate that overlap-related products consistently accounted for the dominant share of total inspected volume throughout the observation period, reflecting high levels of material retention within the plywood manufacturing system. As illustrated in Figure 1, retained output remained substantially higher than downgraded outputs (UTY and UTY-A) across all observation periods. In period 1, the total inspected volume reached approximately 1962.65 $m^{3,}$ of which 1785.45 $m^3$ were retained as OVL products, while only 109.43$m^3$ and 64.51$m^3$ were categorized as UTY and UTY-A, respectively. Similar dominance of retained output was also observed in Periods 2 and 4, suggesting that the production system maintained a relatively high level of material recovery during the observation period.

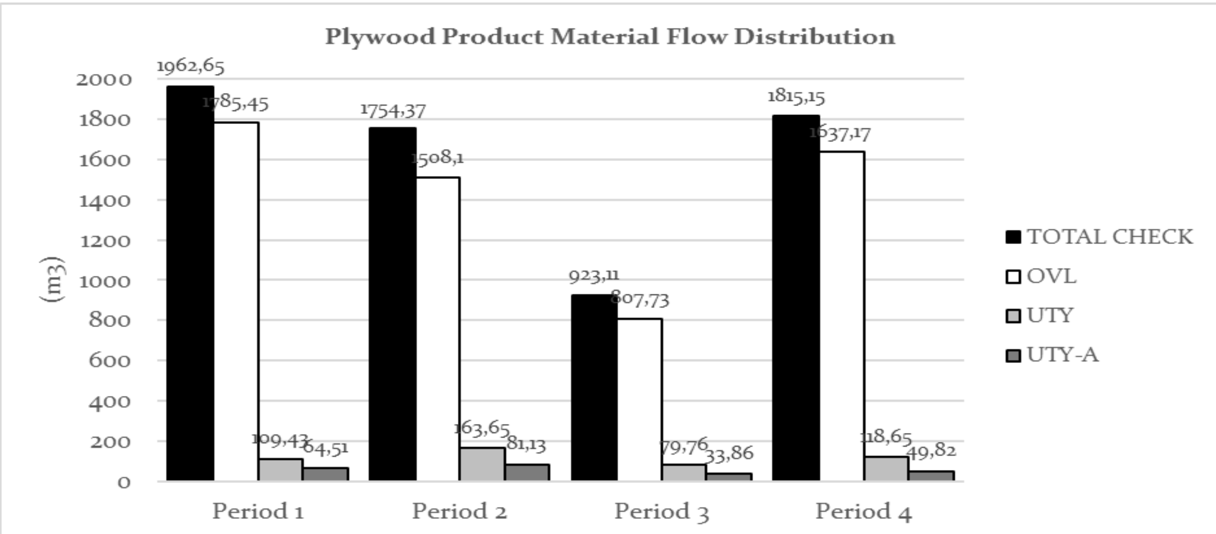


**Figure 1**. Temporal distribution of total inspected volume, retained output (OVL), and under-thickness deviations (UTY and UTY-A) during the observation period.

High recovery rates are commonly reported in plywood manufacturing systems where veneer processing efficiency and panel manufacturing operations are well controlled. Studies have shown that veneer recovery during rotary peeling and subsequent panel assembly processes plays a crucial role in determining overall plywood yield and material utilization efficiency (Kewilaa, 2007). Similar patterns of high retained output have been reported in plywood manufacturing studies where efficient veneer utilization and controlled pressing conditions contribute to improved recovery rates and product yield (Syafii & Novari, 2021). Although the absolute inspected volume varied across months, the retained proportion remained relatively high, indicating a stable capacity of the production system to maintain forest-derived wood material within the productive flow.

Minor fluctuations in retained proportions were observed across months, with lower retention occurring during periods characterized by increased under-thickness deviations. This pattern indicates that primary yield is not static, but responds to changing production conditions over time. Such temporal dynamics highlight the importance of evaluating efficiency performance across multiple observation periods rather than relying on single-point measurements (Wellington et al., 2022).

**Material Loss and Relative Efficiency Indicators**

Material loss associated with under-thickness deviations constituted a relatively small proportion of the total inspected volume in all observation periods. However, when expressed as relative indicators, these losses reveal meaningful differences in efficiency performance across months. A summary of retained and lost material proportions, along with derived efficiency indicators, is presented in Table 1.

**Table 1.** Retained material proportion, material loss, and derived efficiency indicators across observation periods.

| Period | Total Check ($m^3$) | OVL ($m^3$) | UTY ($m^3$) | UTY-A ($m^3$) | Retained (%) | Lost (%) | YVI | LII |
|---|---|---|---|---|---|---|---|---|
| 1 | 1962.65 | 1785.45 | 109.43 | 64.51 | 90.97 | 8.86 | 0.06 | 0.10 |
| 2 | 1754.37 | 1508.10 | 163.65 | 81.13 | 85.96 | 13.95 | | 0.16 |
| 3 | 923.11 | 807.73 | 79.76 | 33.86 | 87.50 | 12.31 | | 0.14 |
| 4 | 1815.15 | 1637.17 | 118.65 | 49.82 | 90.19 | 9.28 | | 0.10 |
| **Mean** | | | | | **88.66** | | | |

*Notes:*
*OVL : Overlap-related products representing retained output meeting thickness specifications*
*UTY : Under-thickness deviation products with significant quality reduction, categorized as downgraded output with limited market value*
*UTY-A : Under-thickness deviation products with minor defects (typically single-sided), resulting in partial quality reduction butretaining higher recovery value compared to UTY*

Although material loss percentages remained below 14% in all months, variations in loss intensity were observed when loss was evaluated relative to retained output. Periods with higher loss intensity coincided with reduced retained proportions, indicating a disproportionate increase in inefficient material use despite modest absolute losses. This finding underscores the importance of assessing loss not only as a fraction of total input, but also in relation to acceptable output.

Previous studies in plywood manufacturing indicate that veneer recovery and conversion efficiency are critical determinants of material utilization performance during production. For example, veneer recovery during rotary peeling commonly ranges between 70–80% of the log volume, with the remaining material becoming waste such as log core and trimming losses (Syafii & Novari, 2021). Similarly, broader analyses of engineered wood products report that veneer yield may vary between 40% and 82% depending on processing conditions, emphasizing the influence of manufacturing parameters on material recovery efficiency (Pramreiter et al., 2023).

The Loss Intensity Indicator (LII) revealed that period 2 exhibited the highest relative loss intensity (0.16), followed by period 3 (0.14), whereas periods 1 and 4 showed lower values (0.10). These differences suggest that production efficiency varied across observation periods despite relatively small variations in absolute material loss. Evaluating loss relative to retained output therefore provides a more sensitive indicator of inefficiencies within the production system.

The Yield Variability Index (YVI) further revealed differences in the temporal stability of material retention. Lower variability values were associated with months exhibiting more consistent retained proportions, while higher variability reflected the sensitivity of efficiency performance to temporal production conditions. These results suggest that efficiency in plywood manufacturing is influenced not only by the magnitude of loss but also by its temporal distribution (Qiu & Cool, 2024).

**Implications for Forest Resource Utilization Efficiency**

Consistently high retained proportions indicate that a large share of forest-derived raw material was effectively converted into acceptable plywood products. From a forest resource utilization perspective, such performance improves conversion efficiency and reduces the need for additional raw material input to achieve production targets (Pramreiter et al., 2023). High recovery rates during veneer processing and panel are therefore essential for improving the overall efficiency of forest resource utilization within the wood-processing sector.

However, observed temporal fluctuations in retained proportions and loss intensity indicate that efficiency gains are not uniform over time. Variations in process performance, raw material characteristics, and operational conditions may influence material recovery during plywood manufacturing, leading to differences in the proportion of acceptable products across production periods (Demirkir et al., 2013)

Even relatively small increases in loss intensity can translate into substantial absolute volumes of wood material when scaled to industrial production levels. Previous studies on material efficiency in industrial systems emphasize that minor inefficiencies at the process level may accumulate into significant resource losses when production volumes are large (Allwood et al., 2013). Consequently, periods of reduced retention may indirectly increase pressure on forest resources by necessitating higher raw material input to achieve the same production output.

Integrating material flow–based indicators into routine efficiency assessment therefore provides a mechanism for linking industrial production performance with forest resource utilization outcomes. Material Flow Analysis (MFA) frameworks have been widely applied to evaluate resource efficiency by quantifying input, retained output, and material losses within industrial systems, allowing production efficiency to be assessed in relation to broader resource sustainability considerations (Wang & Haller, 2024).

**Relevance to Sustainable Forest Management**

Evaluating primary yield and material loss through inspection-based material flow indicators offers a practical and replicable approach for assessing industrial wood utilization efficiency. By emphasizing material retention, temporal stability, and loss intensity, the proposed framework supports a more nuanced understanding of how manufacturing performance influences demand on forest resources. Previous studies have emphasized that improving material efficiency in industrial processing systems can significantly reduce the overall demand for primary raw materials and improve resource sustainability outcomes. (Khan et al., 2024).

Such an approach complements conventional quality control metrics by extending their relevance beyond product conformity toward resource efficiency considerations. In wood-based panel industries, improving production efficiency and minimizing processing losses are widely recognized as important strategies for enhancing the sustainability of forest resource utilization (Çiçekler & Tutuş, 2023). When applied consistently over time, these indicators can inform strategies aimed at improving industrial processing efficiency while contributing to broader objectives of sustainable forest management

## CONCLUSION

The findings confirm that primary yield in plywood manufacturing remains consistently high while exhibiting observable temporal variation across production periods. These fluctuations demonstrate that material retention performance is dynamic and influenced by changing operational conditions rather than being a fixed efficiency attribute. Although downgraded proportions were comparatively limited, their relative changes over time indicate that small shifts in retention performance may translate into substantial material implications at industrial scale. By applying a material flow–based analytical perspective to routine inspection data, this study expands yield evaluation beyond static quality metrics toward an assessment of retention stability and loss intensity within a bounded production system. The proposed framework offers a practical approach for integrating temporal efficiency monitoring into industrial performance evaluation and may be extended to other wood-based manufacturing systems to support more systematic resource utilization assessment over time.

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