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Optimization of eucalyptus replanting schedules: A dynamic model for efficient land use and workforce allocation

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ABSTRACT

This study develops a dynamic scheduling model aimed at optimizing eucalyptus replanting activities within the pulp and paper industry. Addressing the growing demand for sustainable raw material supply, the model integrates the full replanting cycle consisting of land preparation, planting, fertilization, maintenance, and harvesting into a unified system that supports effective land use and workforce allocation. Through simulations involving varying compartment sizes of 8, 9, and 10 hectares and labor configurations from 11 to 20 workers, the study identifies that a replanting unit of 8 hectares with 20 workers yields the shortest harvest age and highest timber output. Model validation via t-tests against real-world data confirms the accuracy of the simulations. Additionally, the model estimates that 2299 compartments are required to meet daily raw material needs of 570 tons and up to 7838 compartments can be scheduled to maximize land utilization. The proposed model serves as a decision support tool for plantation managers, enabling more efficient scheduling, sustainable resource management, and alignment between operational cycles and factory demand. The findings suggest a replicable and scalable framework that enhances productivity while maintaining ecological integrity, supporting the long-term viability of industrial eucalyptus plantations.

Keywords: eucalyptus replanting, scheduling model, land optimization, workforce allocation.

INTRODUCTION

Eucalyptus plantations in Indonesia have expanded rapidly, covering approximately 2.5 million hectares and playing a crucial role in supplying raw materials to the pulp and paper industry, one of the largest globally. In 2022, Indonesia's pulp production capacity reached 12.13 million tons per year, while paper production capacity was 18.26 million tons (Bright Indonesia, 2022). This sector contributes significantly to the national economy, accounting for 0.67% of the country's GDP in 2021 and generating foreign exchange earnings of USD 7.5 billion (CRI Report, 2023; Bright Indonesia, 2022). The pulp and paper industry relies heavily on eucalyptus and acacia plantations, which supply around 50% of the total industrial wood production. Since 2015, all wood for the pulp and paper industry has been sourced from plantations rather than natural forests (NZIF, n.d.). In 2022, wood consumption for pulp production surpassed 46 million cubic meters, predominantly from intensively managed eucalyptus and acacia plantations in Sumatra and Kalimantan (Trase Earth, 2022). Additionally, the export of pulp and paper products plays a significant role in Indonesia's trade, with 2023 exports reaching 6.2 million tons of pulp and 5.3 million tons of paper, reflecting year-on-year growth of 16.9% and 10.4%, respectively (Permatabank, 2024).

Locally, the pulp and paper industry is a significant source of employment, particularly in rural areas where eucalyptus plantations are located. These plantations not only create jobs in forest management but also provide income for local communities through related activities such as planting, harvesting, and transportation (Trase Earth, 2022). The economic benefits also extend to downstream industries, including the manufacturing of paper products, which boosts local economies by supporting a range of businesses and services.

The industry's economic importance is also reflected in its substantial export volume, with Indonesia exporting millions of tons of pulp and paper annually. In 2023, the country exported 6.2 million tons of pulp and 5.3 million tons of paper, marking significant year-on-year growth (Permatabank, 2024). This export activity not only strengthens Indonesia's trade balance but also reinforces its position as a key player in the global pulp and paper market.

The importance of systematic replanting cannot be overstated, as its irregularity directly impacts the continuity of raw material supply for production. Without timely replanting, plantations face the risk of running out of wood, undermining the pulp and paper industry's efficiency. Several factors, such as land availability, environmental conditions, workforce allocation, and management practices, significantly influence the replanting process. Research by Sembiring and Napitupulu (2025) emphasizes the critical role of timely replanting and balanced fertilization in optimizing eucalyptus plantation productivity. Additionally, studies on land use dynamics in Mediterranean forest areas reveal that shifts in land cover patterns highlight the necessity for sustainable land management strategies tailored to forest ecosystems (Ghouldan et al., 2024) Unfortunately, the absence of a standardized and integrated replanting model has resulted in inefficiencies in land use, misalignment between harvesting and replanting cycles, and suboptimal production outcomes (Bose, et al., 2019).

Sustainable replanting practices are critical not only for ensuring a continuous supply of raw materials for the pulp and paper industry but also for safeguarding the environment and biodiversity. Improper replanting can lead to significant negative consequences, such as soil degradation, loss of soil fertility, and the disruption of ecosystems, which may threaten long-term environmental stability (Sembiring et al., 2020). Integrating environmental and climate considerations into plantation scheduling reflects a growing trend in industrial management frameworks, as shown in studies on industrial zones such as Aït Melloul in Morocco (Youssef et al., 2023). On the other hand, sustainable replanting practices support ecological balance by maintaining soil health, enhancing biodiversity, and contributing to the overall sustainability of forest ecosystems (Kuru and Wood, 2018). Evaluating the environmental implications of plantation activities can benefit from life cycle assessment (LCA) methodologies, which offer structured insights into resource use and environmental burdens throughout the process (Sudarno et al., 2024). To achieve these goals, it is essential to develop optimized replanting schedules that account for both environmental and operational factors. Therefore, addressing these challenges through an effective scheduling model is crucial to ensure the long-term sustainability of eucalyptus plantations. The following research questions are proposed to explore this issue further:

1. What is an effective scheduling model for successive eucalyptus replanting activities that ensures long-term sustainability on an annual basis?
2. How can the optimal size of a productive land compartment be determined as a scheduling unit for replanting activities, considering available resources?
3. How can replanting schedules be optimized to align with the plant's demand while ensuring efficient utilization of available land resources?

While a growing body of research exists on land-use efficiency in urban and agricultural contexts (He et al., 2016; Xie and Wang, 2015; Zhao and Fan, 2020), these models often fail to capture the unique complexities of dynamic land use in forestry systems, where factors such as replanting cycles, environmental conditions, and resource management play critical roles. Eucalyptus plantations, for example, require regular cycles of harvesting and replanting, but current models fail to account for the synchronization of these cycles with land compartment sizes and workforce allocation. Previous studies in forestry have modeled biomass growth and hydrological factors (Ouyang et al., 2021; Silva et al., 2021), but few have integrated these models into a dynamic, holistic framework that addresses the unique operational constraints of eucalyptus plantations.

The gap in research regarding sustainable replanting practices exists due to several operational complexities, such as the large areas of land involved in eucalyptus plantations and the varying factors that influence replanting schedules. The vast plantation areas, often spanning millions of hectares, make it challenging to manage replanting efficiently. Additionally, factors such as land availability, synchronization of harvesting and replanting cycles, and workforce allocation create significant challenges (Prescott, 2023). These issues contribute to a lack of standardized models that can effectively address the complexities of replanting in large-scale industrial plantations. This study is crucial because it aims to fill this research gap by developing a dynamic scheduling model that optimizes land use and resource allocation, ensuring sustainable replanting practices in industrial forestry (Sembiring et al., 2020).

Due to operational challenges such as misaligned replanting and harvesting cycles, as well as resource shortages, these issues lead to inefficiencies in resource use, impacting the timely availability of raw materials for pulp and paper production. Companies often struggle to balance continuous wood supply with environmental constraints, including land use and workforce management (Griffin, 2024). Misalignment between harvesting and replanting schedules can exacerbate resource shortages, resulting in delays that negatively impact production efficiency. Addressing these challenges through improved scheduling models is essential for ensuring the sustainable and efficient management of eucalyptus plantations and securing a steady raw material supply for the industry (Sembiring et al., 2020).

A literature review on replanting practices in the pulp and paper industry highlights several key factors that influence the effectiveness of replanting programs. Numerous studies emphasize the importance of synchronizing replanting and harvesting cycles to ensure a continuous supply of raw materials. For instance, Sembiring et al. (2020) discuss how improper replanting can lead to soil degradation and a reduction in biodiversity, which in turn affects long-term plantation productivity. Similarly, Giménez, et.al (2012) highlight operational challenges, such as misaligned schedules and resource shortages, which often disrupt the balance between land use and workforce management in eucalyptus plantations.

Research by Hutapea et al. (2023) suggests that sustainable replanting practices are crucial for maintaining soil fertility and promoting the health of forest ecosystems. In contrast, studies like those by Zabid et al. (2018) and (Arık, 2021) emphasize the role of dynamic models in optimizing replanting schedules, particularly in large-scale plantations, to reduce inefficiencies and increase overall productivity. These models help address the challenges posed by aging plantations and resource limitations by providing solutions that integrate workforce management, land use, and replanting cycles.

The literature further emphasizes that adequate replanting can enhance both economic and environmental outcomes, with studies such as those by Khanal and Straka (2020) advocating for structured planning to optimize resource allocation in industrial forests. However, gaps remain in integrating these practices into a unified model that can account for the complex dynamics of eucalyptus plantation management.

This study aims to fill this gap by introducing a dynamic optimization model that integrates land compartment sizes, workforce allocation, and replanting schedules. By considering the temporal dimensions of harvesting and replanting cycles, this model enables better alignment between land use and workforce deployment, thereby enhancing replanting efficiency. The proposed model presents a novel decision-support tool for plantation managers, enabling them to optimize resource allocation and ensure the sustained productivity of eucalyptus plantations. Unlike previous models, which often focus on static or isolated factors, this integrated approach offers a more comprehensive solution to the operational challenges of eucalyptus forestry, enhancing both sustainability and productivity.

This research aims to design a scheduling model for eucalyptus replanting that supports sustainability and efficiency in resource management. Specifically, the study seeks to:

1. Determine the most productive compartment area for replanting, based on simulation results from compartment sizes of 8, 9, and 10 hectares.
2. Develop an effective scheduling model that utilizes available resources for replanting activities over multiple years.
3. Optimize scheduling to meet the needs of the pulp and paper plant while ensuring the efficient use of land resources.

METHODOLOGY

This study develops a dynamic scheduling model to optimize the replanting process of eucalyptus plantations. The methodology relies purely on computer modelling and theoretical simulations to simulate the replanting activities, land use, and workforce allocation. No physical fieldwork or data collection occurred in this study. Instead, existing field data from previous studies were used as input to validate the model's predictions. This theoretical approach ensures that the model is scientifically rigorous and can be applied to various plantation scenarios (Sembiring et al., 2020).

Model development and input data

The dynamic scheduling model simulates the full replanting cycle, which includes land preparation, planting, fertilization, weeding, maintenance, and harvesting. The model was developed based on theoretical assumptions about eucalyptus plantations, and input data were drawn from existing field data available in published studies (Griffin, 2024; Kuru and Wood, 2018). These data provided the following input parameters for the model:

- Labor requirements – the number of workers and the time taken per task (e.g., slashing, planting).
- Time data – the time taken per hectare for each activity (planting, slashing, fertilization).
- Timber yield – the amount of timber produced per hectare at the time of harvesting.
- Replanting schedules – the timing of each stage of the replanting process, including when the next phase starts (e.g., planting, maintenance, harvesting).

These theoretical assumptions, validated by existing literature and previous empirical studies, helped form the basis for the simulation process.

The model is represented through an input-output diagram, which illustrates the flow of activities and interactions between stages, allowing for easy tracking of resource usage, time allocation, and workforce engagement. The goal is to optimize land use and workforce distribution while addressing challenges such as land allocation, availability, labor, and the timing of replanting activities. The cycle begins with land preparation (preplant slashing and spraying), followed by planting, fertilization, weeding, and ongoing plant maintenance. The final stage involves harvesting, including felling and prebunching, marking the completion of one cycle and the commencement of the next. The input output diagram for one replanting cycle is shown in Figure 1.

The goal of the model is to optimize both land use and workforce distribution, addressing challenges such as land allocation, labor availability, and the timing of replanting activities. The replanting cycle begins with land preparation (preplant slashing and spraying), followed by planting, fertilization, weeding, and ongoing plant maintenance. The final stage involves harvesting, which includes felling and pre bunching, marking the completion of one cycle and the start of the next.

Sub models for replanting activities

The model divides the replanting process into nine distinct sub-models, each focusing on a specific stage of the cycle. Each sub model includes input parameters, process steps, and output results, which are used to simulate the replanting process. The nine sub models are as follows:

- Preplant slashing – the initial step in land preparation, where vegetation is cleared to make space for new seedlings.
- Preplant spraying – treating the land with herbicides to control competing vegetation.
- Planting – the process of planting eucalyptus saplings into the prepared land.
- Fertilization (base fertilization) – applying fertilizers to promote optimal growth.
- Blanking (replanting or filling gaps**)** – replanting seedlings in areas where initial saplings have failed.
- Manual circle weeding – manual weeding around each eucalyptus sapling.
- Plant maintenance – ongoing care, including pest control, irrigation, and additional fertilization.
- Felling – the process of cutting down mature eucalyptus trees for harvesting.
- Prebunching – clearing branches and leaves from felled trees to prepare them for transportation and processing.

Each sub model is designed based on prior studies and expert opinions in plantation management, ensuring that the replanting process is efficient and interconnected.

Model parameters and data inputs

This section outlines all key parameters used in the dynamic scheduling model, including land compartment sizes, labor configurations, task durations, and timber yield estimates. These parameters serve as the primary inputs for the simulation process. The model parameters can be seen in Table 1.

These parameters were input into the model to simulate the full replanting cycle, which includes

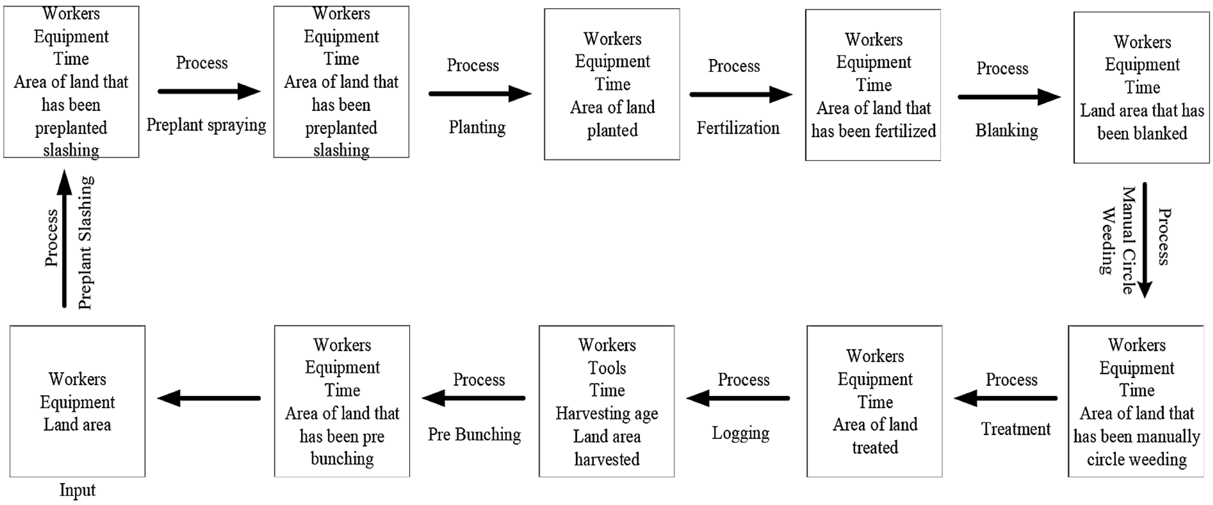

Figure 1. Input output diagram of one replanting cycle

tasks such as land preparation (preplant slashing and spraying), planting, fertilization, maintenance, and harvesting.

Simulation process

The model was run using theoretical simulations based on three different land compartment sizes (8, 9, and 10 hectares) and varying workforce allocations (from 11 to 20 workers per compartment). Key parameters for simulation:

- Land compartment size – three land sizes were tested: 8, 9, and 10 hectares to evaluate the impact of compartment size on replanting efficiency.
- Workforce configuration – the number of workers per compartment was varied from 11 to 20 to analyze the effect of labor allocation on replanting and harvesting outcomes.

The simulations were conducted to predict the following:

- Harvest age – how long it takes for trees to mature based on different configurations of land area and workforce.
- Timber yield – the amount of timber produced under different conditions.

The outputs of the simulations, which were theoretical predictions, were used to assess the model's effectiveness and the impact of various configurations on plantation productivity. These results were then compared to published data to validate the theoretical model.

Data analysis and statistical testing

To assess the reliability of the model, t-tests were conducted to compare the simulated results with actual field data. The simulated data obtained from the model were compared with published field data available in previous studies (Griffin, 2024). The following steps were taken:

- Simulated data – data obtained from the theoretical simulations, including predicted harvest age and timber yield for various configurations.
- Field data – actual data from published studies regarding harvest age and timber yield.
- Statistical methods – paired t-tests were applied to compare the simulated values with

Table 1. Model parameters and descriptions

Parameter	Description	Value range	Source/Assumptions
Land compartment size	Area of the land compartment used for replanting	8, 9, 10 hectares	Based on theoretical assumptions and previous studies
Number of workers	The number of workers allocated per compartment	11–20 workers	Assumed based on standard labor configurations
Time per task	Time taken per hectare for each task (slashing, planting, etc.)	Varies (e.g., 3 days for slashing)	Field data from previous studies
Timber yield	Amount of timber produced per hectare at harvest	10–12 tons/ha/year	Based on field data from plantations

the actual values to determine if the differences were statistically significant.

The significance level of 0.05 was used for the analysis (Sembiring et al., 2020).

T-test procedure and dataset

A paired t-test was performed to compare the means of simulated harvest age and actual harvest age, as well as simulated timber yield and actual timber yield, for each land compartment size (8, 9, and 10 hectares). The null hypothesis (H_0) stated that there was no significant difference between the simulated and actual data.

A significance level of 0.05 was used. If the p-value was greater than 0.05, the null hypothesis was accepted, indicating that the simulation results were consistent with actual data. The purpose of this stage was to ensure the model's accuracy and reliability, confirming that the simulation outputs closely aligned with actual plantation data.

By simulating various scenarios, the methodology aimed to determine the optimal replanting schedule that would minimize harvest age and maximize timber output while considering labor constraints and land availability (Sembiring et al., 2020). However, the comparison was done against real-world data from existing literature rather than field data collected specifically for this study.

This study is based on theoretical modeling and computer simulations rather than fieldwork. The goal of the study was to develop an optimized scheduling model using simulations based on existing practices, with no direct data collection or real world observations from actual eucalyptus plantations.

RESULTS AND DISCUSSION

This section presents the theoretical results derived from the simulations and their analysis, focusing on the relationship between land compartment size, workforce allocation, timber yield, and harvest age. These results are theoretical predictions made by the dynamic scheduling model, which were validated through comparisons with data.

Labor requirements – number of workers and time per task

1. Land preparation (slashing and spraying)
- Task – preplant slashing (cutting down vegetation) and spraying (herbicide application).
- Number of workers – 10 workers per hectare.
- Time per hectare:
  - Slashing: 3 days per hectare (based on typical labor efficiency in medium sized plantations).
  - Spraying: 2 days per hectare.
- Total time: 5 days per hectare.

2. Planting
- Task – planting eucalyptus saplings.
- Number of workers – 12 workers per hectare.
- Time per hectare:
  - Planting: 4 days per hectare (depending on worker skill and sapling spacing).
- Total time – 4 days per hectare.

3. Maintenance (weeding, fertilization, pest control)
- Task – ongoing care of the plants to promote growth (weeding, fertilization, pest control).
- Number of workers – 8 workers per hectare for periodic maintenance.
- Time per hectare:
  - Weeding – 1 day per hectare (twice a year).
  - Fertilization – 2 days per hectare (once a year).
  - Pest control (if needed) – 1 day per hectare (once a year).
- Total time – 4 days per hectare annually.

4. Harvesting
- Task – felling mature eucalyptus trees and preparing them for transport (pre-bunching).
- Number of workers – 10 workers per hectare.
- Time per hectare:
  - Felling – 3 days per hectare.
  - Pre-bunching – 2 days per hectare.
- Total time – 5 days per hectare.
- Time data – the time required per hectare for each activity; time taken for each replanting and maintenance activity per hectare.
- Timber yield – amount of timber produced per hectare at the time of harvesting

Recapitulation of time data for each activity can be seen in the Table 2. Timber yield is often influenced by factors such as soil quality, climate, and management practices. Data from observation of timber yield eucalyptus plantations:

1. Yield per hectare.
- Age at harvest – 7 years (for typical fast growing eucalyptus species).

- Average yield – 10–12 tons per hectare per year, depending on tree density and soil quality.
- Total yield at harvest – after 7 years, a plantation produce around 70–84 tons per hectare at the time of harvesting.
- Replanting schedules – the timing of each stage of the replanting process.

Eucalyptus replanting cycle involves the following stages and recapitulation of stages for eucalyptus replanting can be seen in the Table 3.

The replanting cycle spans 7 years from planting to harvesting. The first maintenance is critical for ensuring proper growth, and subsequent maintenance stages are generally conducted annually until harvest. Replanting activities are simulated starting from preparation, planting, maintenance, and harvesting. The following section presents the example of simulation model.

2. Planting.

Planting activities in this study consist of preplant slashing, preplant spraying, planting, basic fertilization, blanking, manual circle weeding, and plant maintenance. For each of these activities, sub models and flow diagrams were built. As an example, a simulation process and formulation of preplant slashing activities will be provided. This will be done for all the activities involved.

Preplant slashing sub model

This activity serves as the initial stage of land preparation, in which vegetation is cleared to enable subsequent planting processes. The primary input for this sub model is land area that has not yet undergone slashing, while the key process parameters include resource availability and the number of workers assigned to the task.

Table 2. Time data for each activity

Activity	Time per hectare (days)
Preplant slashing	3 days
Preplant spraying	2 days
Planting	4 days
Weeding (annual)	1 day
Fertilization (annual)	2 days
Pest control (annual)	1 day
Felling (harvesting)	3 days
Prebunching (harvesting)	2 days

Figure 2 functions not only as a visual representation of this operational flow but also as a reference framework for simulation. It provides a structured sequence of activities along with corresponding input-output elements for each operational cycle, enabling systematic tracking of process efficiency. The slashing process begins with the entry of data related to the total area to be processed, which subsequently informs the calculation of slashing coverage, resource requirements, and execution time. The simulation submodel for the preplant slashing activity is shown in Figure 2.

Next, in the preplant spraying sub model, the model input is land that has not been sprayed with chemicals. The input parameter is the land area. For preplant spraying activities (process), the parameters that influence are the availability the number of workers in the area.

In the manual circle weeding sub model, the model input is land that has not been subjected to manual circle weeding. The input parameter is the land area. For manual circle weeding activities, the influencing parameters are workers. Maintenance activities consist of young plant maintenance and stand maintenance. Young plant maintenance activities include weeding out other pest plants and fertilization. Stand maintenance activities include the removal of nuisance plants, pruning branches to improve stem quality through increasing the length of the branch free trunk, and thinning to create optimal growing space. Harvesting activities are divided into logging subsystems and prebunching subsystems (Hutapea et al., 2023). In the pre bunching sub model, the model input is land that has not been pre bunched. The input parameters are land area, and pre bunching workers.

Simulation of one cycle

Using AnyLogic software version 8.3.3, Figure 11 displays a simulation of all the activities, referred to as one cycle. One replanting cycle starts from land preparation activities (preplant slashing), preplant spraying, planting, basic fertilization, blanking (insertion), manual circle weeding, plant maintenance, and the harvesting stage, namely felling and pre-bunching. Figure 3 shows a simulation of one replanting cycle. Table 4 shows the simulation formulation for one replanting cycle.

Table 3. The timing of each stages for eucalyptus replanting

Stage	Duration (months)	Notes
Preplant slashing	1 month	Completed before planting, including site clearing.
Preplant spraying	0.5 month	Completed shortly after slashing.
Planting	1 month	Planting is done after slashing and spraying.
First maintenance (weeding & fertilization)	3 months after planting	Initial weeding and basic fertilization.
Second maintenance (weeding & pest control)	6 months after planting	Weeding and pest control measures to ensure growth.
Annual maintenance	Every year until harvest	Weeding, fertilization, and pest control, if needed.
Harvesting	7 years (from planting)	Felling and prebunching mature trees.

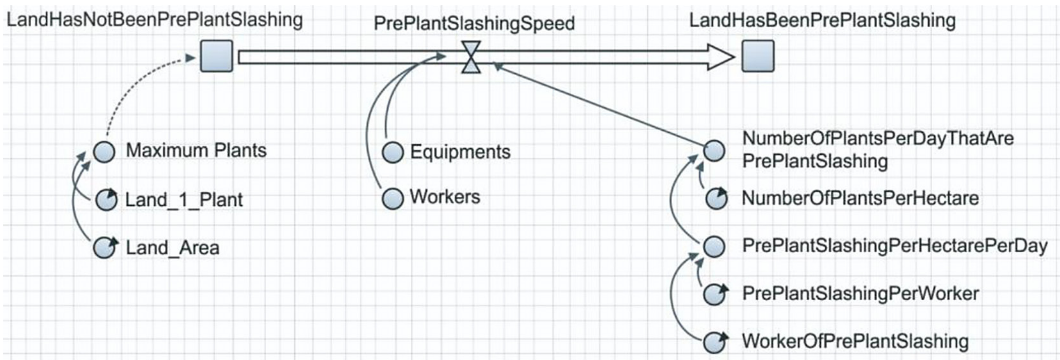

Figure 2. Simulation design of preplant slashing activities

Comparison of actual data and simulation results

Based on the data and simulation results obtained, a comparison is made between the data and simulation results. The comparison needed to compare actual data patterns and simulation results patterns.

Comparison of timber production for land areas of 8, 9, and 10 hectares

To determine an effective replanting schedule, a comparison of results was made between land areas of 8, 9, and 10 hectares.

1. Comparison of timber production for land areas 8 and 9 hectares. To test the difference in timber production for land areas 8 and 9 hectares, a hypothesis is formed, namely:

H_0: There is no difference between timber production for land areas of 8 and 9 hectares.

Based on the timber production data for the land area of 8 and 9 hectares in the Appendix, the Chi-Square test was conducted. The test results are shown in Figure 4.

It can be seen that the Chi-Square value is 0.283, which is above 0.05. Therefore, H0 is rejected, indicating a difference in timber production between the land areas of 8 and 9 hectares.

2. Comparison of timber production between land areas 8 and 10 hectares. The same procedure was followed as when testing the difference in timber production for land areas of 8 and 10 hectares. The initial hypothesis in this section is:

H_0: There is no difference between timber production for land areas of 8 and 10 hectares. Figure 5 shows the results of this test.

It can be seen that the Chi-Square value is 0.242, which is above 0.05. Therefore, H0 is rejected, indicating that there is a difference in timber production between the land areas of 8 and 10 hectares.

3. Comparison of timber production between land areas 9 and 10 hectares. The same procedure was followed as when testing the difference in timber production between land areas 8 and 9 hectares. The initial hypothesis in this section is:

H_0: There is no difference between timber production for land areas 9 and 10 hectares. The results of this test are shown in Figure 6.

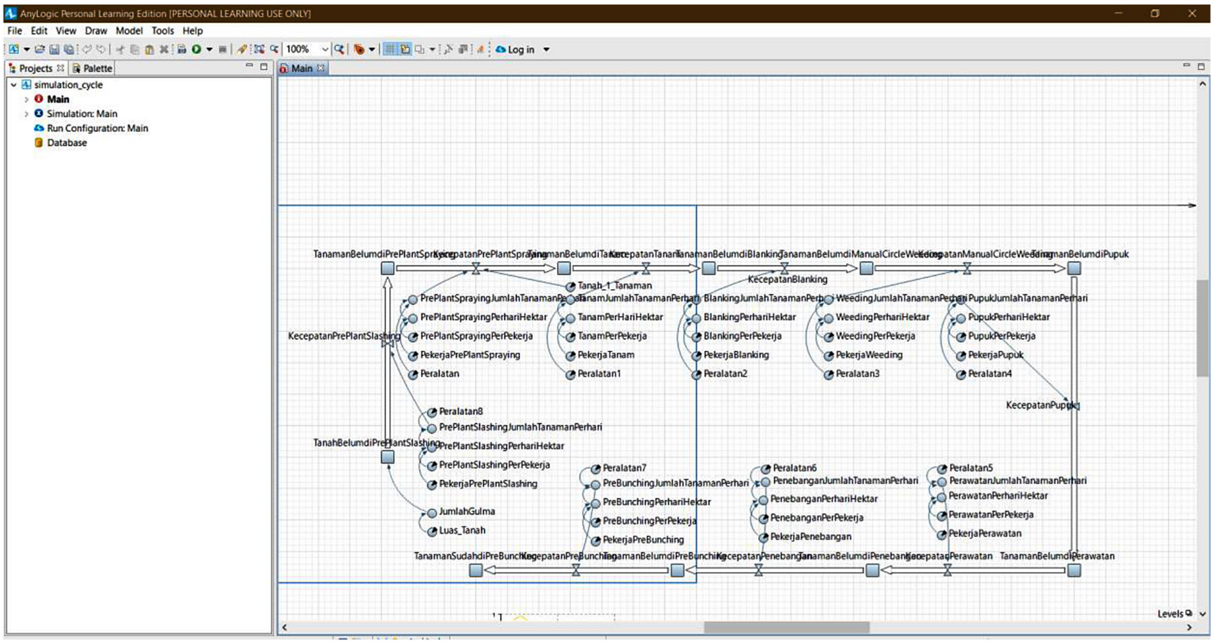

Figure 3. Simulation of one replanting cycle. Formulation of one cycle

It can be seen that the Chi-Square value is 0.242, which is above 0.05. Therefore, it can be concluded that H_0 is rejected, indicating a difference in timber production between the land areas of 9 and 10 Hectares.

Results of the statistical testing

The t-test results showed that the simulated harvest age and timber yield were statistically similar to the actual field data for each land compartment configuration. The p-values for all comparisons were greater than 0.05, indicating that the differences between the simulated and real data were not statistically significant. This validation process confirmed that the model's predictions were accurate and reliable for use in optimizing replanting schedules.

Model verification and validation

To ensure the accuracy and reliability of the model, two key processes: verification and validation were conducted.

1. Verification – the verification process ensures that the model operates without errors and produces logically consistent results. The accuracy achieved by checking for discrepancies or errors during simulation runs. The model was considered verified when it produced outputs without system errors or warnings.
2. Validation – validation was conducted by comparing the model's simulated outcomes (e.g., harvest age and wood production) with actual data from eucalyptus plantations. Statistical tests, particularly t-tests, were used to compare the simulated results with real-world data on harvest age. The null hypothesis (H0) was tested to determine whether there was a significant difference between the simulated harvest age and the actual harvest age. If the test result showed no significant difference, the model was considered valid.
3. Model verification – model verification ensures that the simulation model has been designed correctly and verifies whether the model allows for simulation. A simulation model that does not produce error notifications and warnings can be simulated (Rahmayanti, 2019). The model verification display with the problem feature is shown in Figure 7. Since the Figure indicates a 'No Problem' status, the model is verified.

Figure 7 presents the problem feature display from the simulation software. This display shows whether the model was verified correctly, based on the error status generated during the simulation run. The problem feature in Figure 15 shows a "No Problem" status, indicating that no errors or inconsistencies were detected in the model's initial verification. This means that the model was

Table 4. One (1) cycle formulation

Name	Type	Value	Description
Soil not yet in pre-plant slashing	Stock	= Number of weeds	Amount of soil that has not been pre-plant slashing (m^2)
Pre-plant slashing speed	Flow	= Pre-plant slashing number of plants per day	Number of trees pre-plant slashing per day by workers (trees)
Soil_1_Plant	Parameter	6	Area of land used for 1 plant (m^2)
Area_Land	Parameter	100000	Area of land not in pre-plant slashing (m^2)
Number of weeds	Dynamic Variable	= Area of land /Land_1_Plant	Weeded land area not yet in pre-plant slashing (m^2)
Pre-plant slashing number of plants per day	Dynamic Variable	= Pre plant slashing per day hectare-(Pre Plant Slashing Per Day Hectare *)	Area of land that is pre-plant slashed per day (m^2)
Pre-plant slashing per day hectare	Dynamic Variable	= Pre planting spraying PerWorker*WorkerPrePlanting Spraying	The area of Land that is pre-plant slashing is 1 hectare per day
Pre-plant slashing per worker	Parameter	167	Weed area that can be cleared per worker (m^2)
Pre-plant slashing worker	Parameter	10	Number of workers (people)
Soil not yet in pre-plant spraying	Stock	0	Amount of soil that has not been pre-plant slashing (m^2)
Pre-plant spraying speed	Flow	= Pre-Plant Spraying Number of Plants per Day	Number of trees pre-plant slashing per day by workers (trees)
Planting speed	Flow	= Planting Number of Plants per Day	Number of trees planted per day by workers (trees)
Plant number of plants per day	Dynamic Variable	= Plant Per DayHectare-(Plant Per DayHectare*1)+(Plant Per DayHectare)	Number of plants that can be planted per day (trees)
Planting per day hectare	Dynamic Variable	= Planting per worker *Planting worker	Number of plants planted in 1 hectare per day
Planting per worker	Parameter	167	Amount of land that can be fertilized per worker (m^2)
Planting Worker	Parameter	10	Number of workers (people)
Plants not yet fertilized	Stock	0	Amount of land that has not been Fertilized (m^2)
Fertilizer speed	Flow	= Plant number of plants per day	Number of trees fertilized per day by workers (trees)
Fertilize number of plants per day	Dynamic Variable	= Fertilizer per day hectare-(Fertilizer per day hectare *4)+(Fertilizer per day hectare*4)	Number of plants that can be fertilized per day (trees)
Fertilizer per day hectare	Dynamic Variable	= Fertilizer per worker*Fertilizer worker	Number of plants fertilized in 1 hectare per day
Fertilizer per worker	Parameter	167	Amount of soil that can be fertilized per worker (m^2)
Fertilizer worker	Parameter	10	Number of Workers (people)
Plants not yet blanked	Stock	0	Amount of unblanked soil (m^2)
Blanking speed	Flow	= Blanking number of plants per day	Number of trees blanked per day by workers (trees)
Blanking number of plants per day	Dynamic Variable	= Blanking per hectare-(Blanking per hectare*2) + (Blanking per hectare)	Number of plants that can be blanked per day (trees)
Blanking per day hectare	Dynamic Variable	= Blanking per worker *Fertilizer worker	Number of plants blanked in 1 hectare per day
Blanking per worker	Parameter	167	Quantity of soil that can be blanked per worker (trees)
Blanking worker	Parameter	10	Number of workers (person)
Plants not yet weeded	Stock	0	Amount of land that has not been Weeded (m^2)
Weeding speed	Flow	= Weeding number of plants per day	Number of trees weeded per day by workers (trees)
Weeding number of plants per day	Dynamic Variable	= Weeding per day hectare-(Weeding per day hectare *3)+(Weeding per day hectare)	Number of plants that can be manually circle weeded per day (trees)

Weeding Per Day Hectare	Dynamic Variable	= Weeding workers *Weeding per worker	Number of manual circle weeding plants in 1 hectare per day
Weeding per worker	Parameter	167	Amount of Land that can be Weeded per worker (m^2)
Weeding worker	Parameter	10	Number of workers (person)
Weeding number of plants per day	Dynamic Variable	= Weeding per day hectare-(Weeding per day hectare *3) + (Weeding per day hectare)	Number of plants that can be manually circle weeded per day (trees)
Weeding per hectare day	Dynamic Variable	= Weeding workers *Weeding per worker	Number of plants in manual circle weeding in 1 hectare per day
Weeding per worker	Parameter	167	Amount of Land that can be Weeded per worker (m^2)
Weeding worker	Parameter	10	Number of workers (person)

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	70.000[a]	64	.283
Likelihood Ratio	40.507	64	.990
Linear-by-Linear Association	.001	1	.981
N of Valid Cases	10		

a. 81 cells (100.0%) have expected count less than 5. The minimum expected count is .10.

Figure 4. Chi-square test results comparison of timber production for land area of 8 hectares and 9 hectares

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	80.000[a]	72	.242
Likelihood Ratio	43.279	72	.997
Linear-by-Linear Association	1.371	1	.242
N of Valid Cases	10		

a. 90 cells (100.0%) have expected count less than 5. The minimum expected count is .10.

Figure 5. Chi-Square test results comparison of timber production for land area of 8 hectares and 10 hectares

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	80.000[a]	72	.242
Likelihood Ratio	43.279	72	.997
Linear-by-Linear Association	5.206	1	.023
N of Valid Cases	10		

a. 90 cells (100.0%) have expected count less than 5. The minimum expected count is .10.

Figure 6. Results of square test comparison of wood production simulation year 2018-2022, land area 9 hectares and 10 hectares

successfully executed without encountering any issues related to logical or computational errors.

The purpose of showing this figure is to verify that the model runs without any issues, ensuring that all input parameters are correctly processed and that the model's simulations are ready for further validation against real-world data. If there were any problems (e.g., conflicting input data or computation errors), they would have been flagged here, and the model would require adjustments before proceeding with the validation step. Figure 7 is not showing a "problem" per se, but rather confirming that no computational errors were present during the simulation. The absence

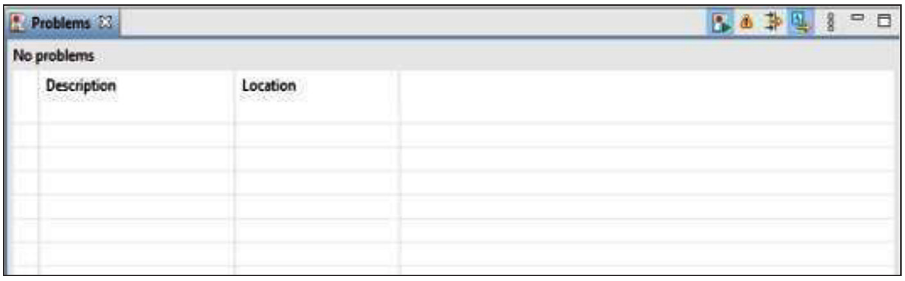

Figure 7. Problem feature display. Source: Anylogic Software

of errors in Figure 7 is a positive sign, validating that the simulation model is functioning as intended and that the results can be trusted for further analysis.

4. Model validation – validation is necessary for simulation results that vary across multiple iterations. The purpose of validation is to determine the level of confidence in the acceptance of average values that represent a range of varying values (Sugiyono, 2000). To test the difference between the simulation results of harvest age and the actual data of harvest age, a hypothesis is formed, namely:

- H0: There is no significant difference between the simulated harvest age and the actual harvest age data.
- H1: There is a significant difference between the simulation results of harvest age and the actual data of harvest age.

The following are the results for the t-test conducted on each land area. The results of the t-test in SPSS for a land area of 8 hectares are shown in Figure 8.

Validation is performed by comparing the simulation results with actual conditions using the t-test. Based on the output, it can be seen that the Sig. Is 0.686, and the t value is 0.419. From the t-test results above, the significance level is: Levene's Test for Equality of Variances is 0.686 > 0.05, indicating that the data variance between the actual data and simulated data on an 8-hectare compartment is homogeneous, or the same. The average comparison test conducted with the T-test shows the calculated t value of 0.419 < 2.228 (t-table value). Decision making through the comparison of the calculated t-value with the t-table indicates that H0 can be accepted, which means that there is no significant difference between the simulation results for a land area of 8 hectares and the actual data on harvest age for the same land area.

The results of the t-test in SPSS for a 9-hectare area are presented in Figure 9.

Validation is performed by comparing the simulation results with actual conditions using the t-test. Based on the output, it can be seen that the Sig. the p-value is 0.977, and the t-value is 0.029. From the t-test results above, the significance level is 0.977, as determined by Levene's test for equality of variances, which is greater than 0.05. Therefore, it can be inferred that the data variance between the actual data and simulated data for a 9-hectare compartment area is homogeneous, indicating that the variances are equal. The average comparison test conducted with the T-test shows the calculated t value of 0.029 < 2.228 (t-table value). Decision making is performed by comparing the calculated t-value with the t-table. If H0 is accepted, it means that there is no significant difference between the simulation results for a land area of 9 hectares and the actual data on harvest age for a land area of 9 hectares. The results of the t-test in SPSS for a 10-hectare area are presented in Figure 10.

Validation is performed by comparing the simulation results with actual conditions using the t-test. Based on the output table above, the Sig. The value is 0.117, and the t-value is 1.755. From the t-test results above, the significance level is: Levene's Test for Equality of Variances is 0.117 > 0.05, indicating that the data variance between the actual data and simulated data on a 10-hectare compartment area is homogeneous, or the same. The average comparison test conducted with the T-test shows the calculated t value of 1.755 < 2.228 (t-table value). Decision-making is performed by comparing the calculated t-value with the t-table. If H0 is accepted, it means that there is no significant difference between the simulation results for a 10-hectare land area and the actual data on harvest age for a 10-hectare land area.

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	44.295	39.387		1.125	.239
	Comparison of Simulation	.271	.647	.147	.419	.686

a. Dependent Variable: Actual Comparison

Figure 8. Results of the t-test on a 1-compartment area of 8 hectares. Source: IBM SPSS Statistics Software

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	59.878	14.826		4.039	.004
	Comparison of Simulation	.007	.245	.010	.029	.977

a. Dependent Variable: Actual Comparison

Figure 9. Test results of the t test on 1 compartment area of 9 hectares. Source: IBM SPSS Statistics Software

Selection of land area and number of workers for eucalyptus plantations

This study explores the relationship between the land area and the number of workers in eucalyptus plantations, specifically focusing on how these factors impact the harvest age and the yield of the plantation. Three land area sizes were considered: 8 hectares, 9 hectares, and 10 hectares. Additionally, the number of workers ranged from 11 to 20 per compartment.
Key findings:

- Impact of workers on harvest age and yield:

The number of workers directly affects both the harvest age and the yield per hectare. For example, on a 10-hectare land with 11 workers, the harvest age is 64.5 months, and the yield is 11.03 tons per hectare per year. As more workers are added, the harvest age decreases, but the yield per worker also changes.

- Comparison of different land areas and workers:

The study compares the harvest age, yield, and production per worker across different land areas and worker numbers.

- For 10 hectare land, with 11 workers, the harvest age is 64.5 months, and the yield is 11.03 tons per hectare per year.
- As the number of workers increases to 20, the harvest age decreases to 63 months, and the yield rises to 11.29 tons per hectare per year.

Harvest age and yield comparison as shown in Table 5 and Figure 11. The results show a clear trend: as the number of workers increases, the harvest age decreases, but the total production per worker also changes. Table 5 and Figure 11 illustrate this relationship, helping to identify the most optimal setup for the plantation.

Figure 11 shows that the shortest harvest age is 62.73 months, with a production of 11.34 tons per hectare per year, achieved on an 8-hectare land with a workforce of 20 workers.

Optimal setup for shortest harvest age and highest yield

Based on the findings, the optimal combination for achieving the shortest harvest age and highest yield is:

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	42.155	10.307		4.090	.003
	Comparison of Simulation	.300	.171	.527	1.755	.117

a. Dependent Variable: Actual Comparison

Figure 10. Test results of the t test on 1 compartment area of 10 hectares. Source: IBM SPSS Statistics Software

- Land area – 8 hectares,
- Number of workers – 20 workers,
- Harvest age – 62.73 months,
- Yield – 11.34 tons per hectare per year.

Replanting schedule and land utilization

The following section outlines the replanting schedule formulated to address two primary objectives: meeting the daily raw material requirements of a pulp mill and optimizing the utilization of available land. These plans are essential to ensure continuous supply and efficient use of resources.

a) Replanting for pulp mill needs – to meet the wood demands of a pulp mill with a capacity of 570 tons per day, 2,299 compartments (8 hectares each) are required for replanting. This is calculated based on the yield of 11.31 tons per hectare per year, or 0.03098 tons per hectare per day.

b) Replanting for land utilization – if 62,698 hectares of land are available, approximately 7,838 compartments need to be planted every day to fully utilize the land. This schedule is shown in Figure 12 and Figure 13.

Table 5. Comparison of harvest age, yield, and total production per person based on land area and number of workers

Land area (ha)	Number of workers	Harvest age	Yield (Ton/ha/year)	Total production per worker (Ton/ha/year)
10	11	64,5000	11,0254522	1,002313836
10	12	64,1667	11,08272727	0,923560606
10	13	64,0334	11,10580427	0,854292636
10	14	63,8334	11,14060052	0,79575718
10	15	63,6000	11,18147275	0,745431516
10	16	63,5334	11,19320567	0,699575354
10	17	63,4334	11,21085129	0,65946184
10	18	63,3000	11,23446551	0,624136973
10	19	63,2667	11,24038462	0,59159919
10	20	63,0000	11,28796296	0,564398148
9	11	64,1667	11,08272727	1,007520661
9	12	63,8667	11,13478601	0,927898834
9	13	63,7667	11,15224778	0,857865214
9	14	63,5667	11,18733613	0,799095438
9	15	63,4334	11,21085129	0,747390086
9	16	63,3667	11,22264598	0,701415373
9	17	63,2667	11,24038462	0,661199095
9	18	63,0000	11,28796296	0,627109053
9	19	62,9667	11,29393859	0,594417821
9	20	62,9334	11,29992055	0,564996028
8	11	63,8667	11,13478601	1,012253274
8	12	63,6000	11,18147275	0,931789396
8	13	63,5334	11,19320567	0,86101582
8	14	63,3667	11,22264598	0,80161757
8	15	63,2667	11,24038462	0,749358974
8	16	63,0000	11,28796296	0,705497685
8	17	62,9667	11,29393859	0,664349329
8	18	62,9000	11,30590885	0,628106047
8	19	62,8334	11,31790451	0,595679185
8	20	62,7334	11,3359458	0,56679729

Figure 11. Comparison between number of workers and harvest age

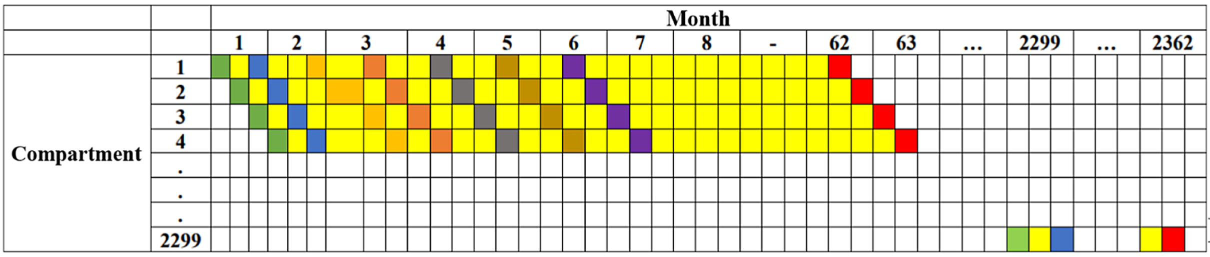

Figure 12. Replanting schedule for raw material needs

Notes

Process	Time (Day)	Month	Symbol
Pre Plant Slashing	5	0,17	
Delay	14	0,63	
Pre Plant Spraying	2	0,70	
Delay	30	1,70	
Planting	10	2,03	
Delay	14	2,50	
Blanking	4	2,63	
Delay	25	3,47	
Manual Circle Weeding	5	3,63	
Delay	21	4,33	
Fertilization	1	4,37	
Delay	30	5,37	
Perawatan	3	5,47	
Delay	1700	62,13	
Harvesting	8	62,40	

Figure 13. Description of the replanting process

Implications and recommendations

Determining the size of eucalyptus replanting compartments, whether 8, 9, or 10 hectares, will help the company plan and organize its operations more efficiently. Based on the results of the study, it was found that for a compartment area of 8 hectares, the age of harvest and the average amount of timber production in units of tons/ha/year are different according to the number of workers, ranging from 11 people, 12 people, to 20 people per compartment. Likewise, for compartment areas of 9 hectares and 10 hectares, the age of harvest and the average amount of timber production differ according to the number of workers, ranging from 11 to 20 people per compartment.

- Eucalyptus replanting strategy – the study recommends that the company use 8-hectare compartments with 20 workers. This setup will result in the shortest harvest age and the highest yield. The study also suggests that with proper planning, this method will help maximize production and meet the factory's wood requirements.
- Land area selection – by selecting a compartment size of 8 hectares and employing 20 workers per compartment, the company can optimize both the harvest age and production yield. This approach provides the most efficient solution for land use and workforce management.

From the research results presented in Table 5, it can be seen that in the 10 hectare compartment:

- If 11 people are used as workers, then the harvest age is 64.5 months, with a production amount of 11.0254522 tons/ha/ year.
- If 12 people are used as workers, then the value of harvest age is 64.1667 months, with a production amount of 11.08272727 tons/ha/ year.
- And so on, until the number of workers used reaches 20 people, the value of harvest age is 63 months, with a production amount of 11.28796296 tons/ha/ year.

Furthermore, through the results obtained in this study, it can be seen that in the 9-hectare land area compartment:

- If 11 people are used as workers, the harvest age value is 64.1667 months, with a production amount of 11.08272727 tons/ha/ year.
- If the amount of labor used is 12 people, then the value of harvest age is 63.8667 months, with a production amount of 11.13478601 tons/ha/year.
- And so on, until the number of workers used reaches 20 people, the value of harvest age is 62.9334 months, with a production amount of 11.29992055 tons/ha/ year.

Meanwhile, through the results obtained in this study, it can be seen that in the 8-hectare land area compartment:

- If the number of used workers is 11 people, the harvest age value is 63.8667 months, with a production amount of 11.3359458 tons/ha/ year.
- If 12 workers are used, the harvest age is 63.6 months, resulting in a production of 11.13478601 tons/ha/ year.
- And so on, until the number of used workers reaches 20 people, the value of harvest age is 62.7334 months, with a production amount of 11.3359458 tons/ha/ year.

The analysis shows that with a land area of 8 hectares and a workforce of 20 workers, the shortest harvest age of 62.73 months is achieved, yielding the highest production of 11.34 tons per hectare per year.

Based on the study's findings, it is recommended to select a compartment size of 8 hectares, with a workforce of 20 people, in order to achieve the shortest harvest age and the highest production yield.

CONCLUSIONS

This study presents a dynamic replanting scheduling model that addresses critical operational and sustainability challenges in eucalyptus-based pulp and paper production. By simulating various land compartment sizes and labor configurations, the model identifies the optimal replanting configuration consisting of 8 hectare compartments supported by 20 workers as the most effective for achieving the shortest harvest age of 62.73 months and the highest timber yield of 11.34 tons per hectare per year. The model's validity is supported through statistical tests confirming alignment with actual harvest age data. Furthermore, the model provides precise estimates for plantation planning, determining that 2299 compartments are necessary to fulfill daily production targets while up to 7838 compartments are required for full land utilization. These findings offer a structured and adaptable framework for plantation managers, facilitating better land and labor planning. Importantly, this model contributes not only to operational efficiency but also to environmental sustainability by promoting timely and synchronized replanting practices. It provides a scalable and practical decision support system that enhances the resilience and productivity of industrial forestry operations.

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