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Sizing an intermediate wood yard to reduce forest logistics costs: applied modeling

Dimensionamento de um pátio intermediário de madeira para reduzir custos de logística florestal: modelagem aplicada

Dimensionamiento de un patio intermedio de madera para reducir los costos de logística forestal: modelización aplicada

Vitória Bianca Lima Dantas – Universidade Federal de Mato Grosso do Sul (UFMS), vitoria_bianca@ufms.br
Fernando Jose Gomez Paredes – Universidade Federal de Mato Grosso do Sul (UFMS), fernando.gomez@ufms.br

Abstract: In wood transport to pulp mills, rainy periods impair the trafficability of internal farm roads and force companies to gravel extensive road networks to secure supply. This study aimed to develop a model for sizing an intermediate wood yard able to reduce the stock kept on farms during the rainy season and, consequently, graveling costs. It is a case study in a pulp forestry company in eastern Mato Grosso do Sul, Brazil, using spreadsheet modeling based on the 2027 supply plan. Scenarios of 30,000, 40,000, 50,000 and 60,000 m³ of capacity were evaluated, considering safety stock, rainfall, transport, and investment and operating costs. The problem was formulated with annual net savings as the objective function and the number of monthly turnovers fixed at two as a constraint. The recommended yard, with 60,000 m³, an area of about 24,100 m² and three log loaders, absorbs 70% of the annual safety stock of 1.7 million m³ and reduces the annual cost of direct shipment from BRL 32.8 million to BRL 25.4 million by avoiding the placement of crushed stone on part of the internal roads. With an investment of BRL 5.2 million, net savings reach BRL 7.3 million per year, with a payback of about 8.5 months. The study showed that the number of log loaders determines the cost of each yard size. The sensitivity analysis confirmed feasibility under 20% variations in the main variables and with the more conservative loader productivity estimate.

Keywords: Forest logistics. Intermediate wood yard. Inventory management. Forest roads. Scenario modeling.

Resumo: No transporte de madeira para fábricas de celulose, os períodos chuvosos comprometem a trafegabilidade das estradas internas das fazendas e obrigam as empresas a cascalhar extensas malhas viárias para garantir o abastecimento. Este trabalho desenvolveu um modelo para dimensionar um pátio intermediário de madeira capaz de reduzir a necessidade de estoque nas fazendas durante a chuva e, com isso, os custos de cascalhamento. Trata-se de um estudo de caso em uma empresa do setor florestal de celulose da região leste de Mato Grosso do Sul, com modelagem em planilha a partir do planejamento de 2027. Foram calculados cenários de 30.000, 40.000, 50.000 e 60.000 m³ de capacidade, considerando estoque seguro, precipitação e custos de implantação e operação. O problema foi formulado com a economia líquida anual como função objetivo e o número de giros mensais fixado em dois como restrição. O pátio recomendado, de 60.000 m³, com cerca de 24.100 m² e três gruas, absorve 70% do estoque seguro anual de 1,7 milhão de m³ e reduz o custo anual de envio direto de R$ 32,8 milhões para R$ 25,4 milhões, ao evitar brita em parte das estradas internas. Com investimento de R$ 5,2 milhões, a economia líquida é de R$ 7,3 milhões por ano, com retorno em cerca de 8,5 meses. O número de gruas define o custo de cada porte de pátio. A análise de sensibilidade confirmou a viabilidade diante de variações de 20% nas principais variáveis e com a estimativa mais conservadora de produtividade das gruas.

Palavras-chave: Logística florestal. Pátio intermediário. Gestão de estoques. Estradas florestais. Modelagem de cenários.

Resumen: En el transporte de madera a las fábricas de celulosa, los períodos lluviosos comprometen la transitabilidad de los caminos internos de las fincas y obligan a las empresas a revestir con grava extensas redes viales para garantizar el suministro. Este trabajo desarrolló un modelo para dimensionar un patio intermedio de madera capaz de reducir la necesidad de

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mantener existencias en las fincas durante las lluvias y, con ello, los costos de revestimiento con grava. Se trata de un estudio de caso en una empresa forestal de celulosa del este de Mato Grosso do Sul, con modelización en una hoja de cálculo a partir de la planificación de 2027. Se calcularon escenarios de capacidad de 30.000, 40.000, 50.000 y 60.000 m³, considerando las existencias de seguridad, la precipitación y los costos de implantación y operación. El problema se formuló con el ahorro neto anual como función objetivo y dos rotaciones mensuales como restricción. El patio recomendado, de 60.000 m³, con aproximadamente 24.100 m² y tres grúas, absorbe el 70% de las existencias de seguridad anuales de 1,7 millones de m³ y reduce el costo anual de envío directo de R$ 32,8 millones a R$ 25,4 millones, al evitar la colocación de piedra triturada en parte de los caminos internos. Con una inversión de R$ 5,2 millones, el ahorro neto es de R$ 7,3 millones anuales, con retorno en aproximadamente 8,5 meses. El número de grúas determina el costo de cada tamaño de patio. El análisis de sensibilidad confirmó la viabilidad ante variaciones del 20% en las principales variables y con la estimación más conservadora de productividad de las grúas.

Palabras clave: Logística forestal. Patio intermedio. Gestión de inventarios. Caminos forestales. Modelización de escenarios.

1. Introduction

The planted forest sector occupies a strategic position in the Brazilian economy, and Mato Grosso do Sul has become the main axis of its expansion. According to the IBGE Plant Extraction and Forestry Production Survey (PEVS), the state's forestry area has increased from 1,459,944 ha in 2024 to 1,902,957 ha in 2025, an increase of 30.3%, of which 99.7% is cultivated with eucalyptus (IBGE, 2026). This progress is associated with the establishment of large pulp mills in the region known as the Valley of Pulp, which demand a continuous and high flow of wood.

In this context, supply logistics is decisive for company competitiveness. Road transport predominates in the sector and accounts for a substantial share of the delivered timber cost, ranging from 38% to 66% of the final acquisition cost depending on distance traveled (SEIXAS; WIDMER, 1993). In addition to transport itself, companies must ensure that the forest road network supports heavy truck combinations, such as double- and triple-trailer combinations, throughout the year.

Road conditions are a known bottleneck in the state. As early as 2017, when the eucalyptus area of Mato Grosso do Sul exceeded one million hectares, representatives of the sector pointed to neighboring roads, alongside transport logistics and infrastructure, as one of the main factors in increasing production costs (HADDAD, 2017). The theme is current: in 2026, the National Traffic Secretariat authorised, as a test for one year, the circulation of 41 hexatrens, compositions up to 60 m long and 250 t of gross weight, on unpaved stretches of state highways in the region, which demonstrates the importance of dirt roads for the flow of wood (OLIVEIRA, 2026).

In the forestry sector, timber travels along two types of road to reach the mill: first, external and internal farm access roads, generally unpaved; then, paved highways. Dirt roads require constant improvement and maintenance, including clay treatment and crushed-stone

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placement, to support heavy truck combinations, representing substantial infrastructure costs for companies (LOPES; MACHADO; SOUZA, 2002; MACHADO, 2013). During heavy rainfall, road trafficability deteriorates, increasing the risk of trucks becoming stuck, making timber removal difficult, and threatening mill supply. In Ribas do Rio Pardo, a municipality in the Vale da Celulose region, rainfall in early 2023 left sections of local roads impassable, and the municipality reported that the problem recurs every summer (MATOS, 2023). Consequently, companies must prepare and maintain a greater length of surfaced roads, increasing infrastructure and operating costs.

One alternative for reducing this dependence is an intermediate wood yard acting as a distribution center between harvesting areas and the mill. In business logistics, such intermediate facilities are used to reduce total system costs despite adding storage and handling costs (BALLOU, 2006). During periods of good road trafficability, timber would be removed from farms in advance and stored in the yard; in rainy periods, the mill would draw on this stock using roads in better condition. This reduces the volume that must be removed from farms during rainfall and, consequently, the length of internal roads requiring gravel surfacing. This study addresses only internal access roads, since reducing gravel surfacing on external access roads could compromise truck passage.

The literature addresses the topics involved in this decision separately: the sizing and costs of yards and intermediate terminals (KONS; LA HERA; BERGSTRÖM, 2020; VÄÄTÄINEN et al., 2021), timber transport and supply logistics (SEIXAS; WIDMER, 1993), and the effects of rain on forest road trafficability and costs (LOPES; MACHADO; SOUZA, 2002; ARRIVABENI, 2021). However, few studies integrate these dimensions to assess intermediate yards as a strategy for reducing internal access road gravel surfacing requirements during rainy periods, especially in eucalyptus forests in the Cerrado of Mato Grosso do Sul. This study therefore asks: what storage capacity of an intermediate yard reduces the need to hold timber stocks on farms during periods of heavier rainfall while maintaining industrial supply and reducing internal road gravel surfacing costs?

The overall objective is to develop a model for assessing different sizing alternatives for a intermediate wood yard, taking into account safety stock, precipitation, transport, operational capacity and deployment and operation costs. The specific objectives are:

a) characterise the current flow of timber supply and the seasonality of rainfall in the region studied;
b) define the operational and cost parameters of transport and intermediate yard;
c) calculate scenarios for the capacity of the yard of 30,000, 40,000, 50,000 and 60,000 m^3;
d) estimate, for each scenario, the required area, equipment fleet, capital expenditure (CAPEX), operating expenditure (OPEX), and potential reduction in gravel surfacing costs;

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e) identify the alternative with a better relationship between cost, capacity and service at the plant.

From a practical point of view, the study provides industry firms with a decision support tool for planning supply in the rainy season. From an academic point of view, it contributes to the area of Logistics and Operational Research in Production Engineering by applying scenario modeling to a real forest supply chain problem.

2. Theoretical framework

This chapter brings together the concepts underpinning the dimensioning of the intermediate yard. Initially, forest logistics and its stages are described in order to locate where the yard fits into the flow of timber (section 2.1). The yard is then presented as a distribution centre, based on enterprise logistics and experience of intermediate terminals (section 2.2). Finally, the relationship between rainfall, forest roads and safety stock is discussed, which defines the problem dealt with in this paper (section 2.3).

2.1 Forest logistics

Forest logistics comprises the planning and execution of timber flows from harvest to consumer unit. In cellulose companies, this chain needs to deliver large volumes continuously because the plant operates uninterrupted and any shortage of raw material compromises production. Generally, the flow of wood follows the following steps:

a) harvesting: felling trees and processing them into logs within the stand;
b) forwarding: moving logs from inside the stand to the roadside;
c) field storage: forming roadside log piles that await transport;
d) loading: placing logs on trucks using forest log loaders;
e) main transport: movement of timber by internal roads, external accesses and highways to the plant;
f) receipt: weighing, unloading and storage in the yard of the factory.

In Brazil, the main transport of timber is carried out almost entirely by truck. Seixas and Widmer (1993) report that, in pulp and wood-panel companies in São Paulo state, transport costs ranged from 38% to 66% of the final delivered timber cost for average distances of 45 to 240 km. They also note that road constraints, such as gradients and sections impassable during rain, affect vehicle selection and total operating costs. The intermediate yard proposed here is positioned between field storage and transport to the mill.

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2.2 Distribution centers and intermediate wood yards

In business logistics, storage balances supply and demand when they occur at different rates. Ballou (2006) treats total logistics costs as the outcome of trade-offs among transport, inventory, and service level: an intermediate facility increases storage and handling costs but can reduce transport costs or shortage risks. Establishing a storage point therefore requires assessing total system costs rather than each activity's individual cost. For timber, this distribution center takes the form of a yard: an area prepared to receive, stack, and dispatch logs, with access suitable for heavy traffic and loading equipment.

Yards or intermediate terminals are storage points located between the harvest areas and the factory. In Finland and Sweden, they are used precisely to deal with periods of low trafficability: during melting and rains, when roads and soils lose support capacity, the wood needs to be stored for longer and is taken to terminals in advance to ensure the continuous supply of industry (VÄÄTÄINEN et al., 2021).

Sizing these inventories involves trade-offs. In a simulation of a Swedish pulp mill wood yard, Kons, La Hera and Bergström (2020) showed that expanding auxiliary storage to approximately 89,000–99,000 m³ would limit the age of stored logs and reduce machine working time. Conversely, Seixas and Widmer (1993) found intermediate yard forwarding uneconomical in their study because additional loading and unloading costs and time exceeded the gains. These findings indicate that yard viability depends on each operation's specific conditions, supporting the use of scenario analysis.

Another relevant factor is how long timber remains in storage. Eufrade-Junior et al. (2021) found that eucalyptus logs stored outdoors during rainy periods had higher final moisture content (36.4%) than those stored during dry periods (31.1%), affecting transported weight and raw-material quality.

2.3 Forest roads rainy periods and safety stock

Forest roads are mostly unpaved and without a sealing layer, making them more vulnerable to water degradation and heavy traffic (ARRIVABENI, 2021). In order to maintain trafficability, a primary coating layer such as crushed stone is applied, the main advantage of which is to reduce the frequency and cost of maintenance (MACHADO, 2013).

Road standards directly affect costs. Lopes, Machado and Souza (2002) showed that, on two-lane roads with primary surfacing, surfacing represents 35%–55% of construction costs, and average vehicle speeds fall from approximately 41 km/h on main roads to 24 km/h on tertiary roads, tending to increase transport costs. Arrivabeni (2021) also found that the maintenance approach, with or without gravel replenishment, directly affects the fleet needed

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to meet demand. These findings reinforce that reducing the length of roads requiring gravel surfacing for rainy periods can generate substantial savings.

Safety stock is the usual means of temporarily overcoming this constraint. Inventory management seeks to maintain enough material to meet demand at the lowest possible cost: safety stock is the portion retained to absorb supply and demand uncertainties, while inventory turnover indicates how often average stock is renewed over a given period (BALLOU, 2006). In pulp mill supply, the main source of supply uncertainty is weather. During rainfall, timber removal from farms is restricted, and the mill depends on stock accumulated in the field, in areas served by gravel roads that still do not guarantee complete reliability, in the mill yard, or in intermediate yards. Safety stock sizing must therefore account for rainy-period duration and intensity, daily mill consumption, and available transport capacity.

3. Method

As regards classification, this research is applied, quantitative, and adopts the case study as a technical procedure, using modelling and scenario analysis, according to the categories of production engineering research described by Miguel (2012). The intermediate yard was modelled as a distribution centre, based on the logistics cost offsetting concepts of Ballou (2006). The case was chosen from a company in the forestry sector located in the eastern region of Mato Grosso do Sul, where the supervised internship was carried out, which allowed access to planning and cost data. However, the model does not depend on the particularities of that company: as it is constructed from parameters (monthly volume, rainy days, yard capacity, crane productivity and unit costs), its application to another company or region requires only the replacement of these parameters. For reasons of confidentiality, the name of the company and the farms was omitted and part of the volume and cost figures were adjusted for proportionality factors. This procedure does not alter the relationships between the variables or the conclusions of the study.

The study followed the operations research modeling stages described by Hillier and Lieberman (2013): problem definition, data collection, parameter definition, model construction, scenario calculation, results analysis, and sensitivity analysis. Operations research applies quantitative methods to support decisions in complex systems. Among its techniques, scenario analysis compares alternatives under the same assumptions, while sensitivity analysis examines how results change when uncertain parameters vary.

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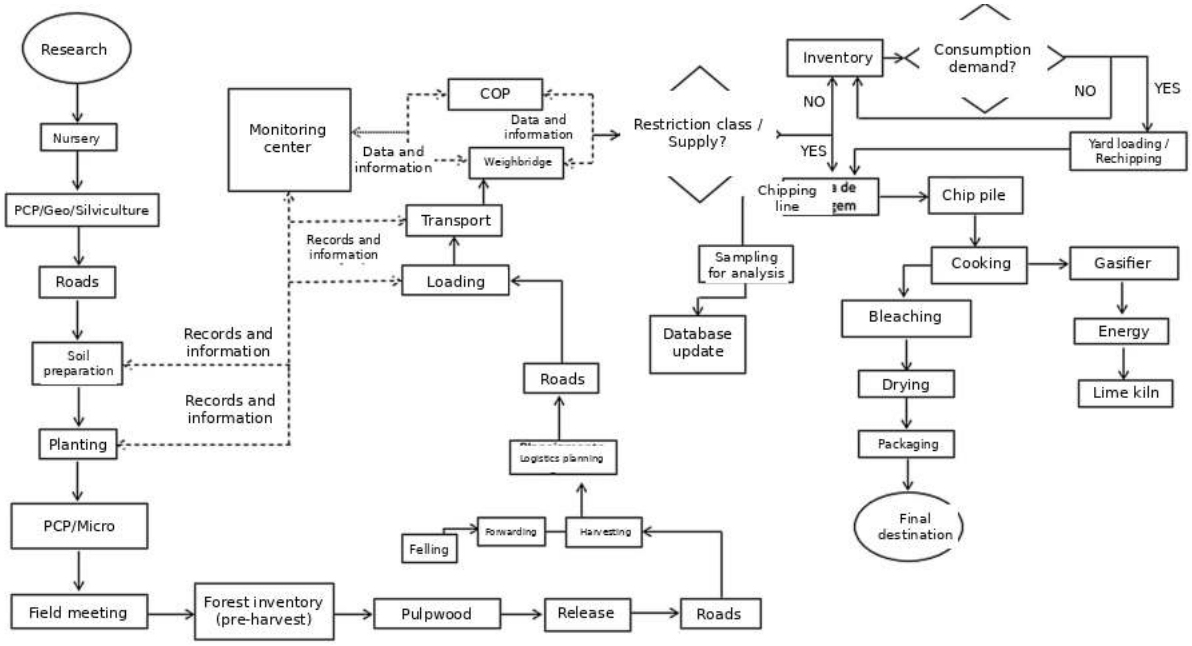
3.1 Problem characterization

Timber flows continuously from the farms studied to the mill, at between 14,400 and 18,600 m³ per day, depending on the month. As the company does not yet have an industrial facility in the state, timber is transported over long distances to the mill, and the volume analyzed represents the share of supply originating from farms in the region. On rainy days, removing timber from the stands depends on internal roads surfaced with crushed stone, referred to in this study as gravel roads. Under the current model, the entire volume needed to supply the mill on rainy days, termed safety stock, is stored on the farms, and the company must gravel the roads providing access to this stock. Figure 1 shows the company's timber supply chain, from seedling production in the nursery to arrival at the mill and processing.

Figure 1 – Flowchart of the timber supply chain of the undertaking studied



Source: drawn up by the author (2026).

In loading planning, each harvesting area has operating alternatives for both dry and rainy periods. On rainy days, areas with fully gravel-surfaced roads are prioritized to ensure trafficability and uninterrupted supply. To maintain these roads, the company uses techniques including embedding aggregate into the road surface, clay soil reinforcement, crushed-stone reinforcement, and soil–crushed-stone mixtures, using material extracted from deposits near operating areas.

The proposed alternative is to transfer part of this stock to an intermediate yard, supplied on dry days and emptied on rainy days, reducing the volume remaining in the field and therefore the extent of roads to gravel. Figure 2 shows how the yard enters the supply

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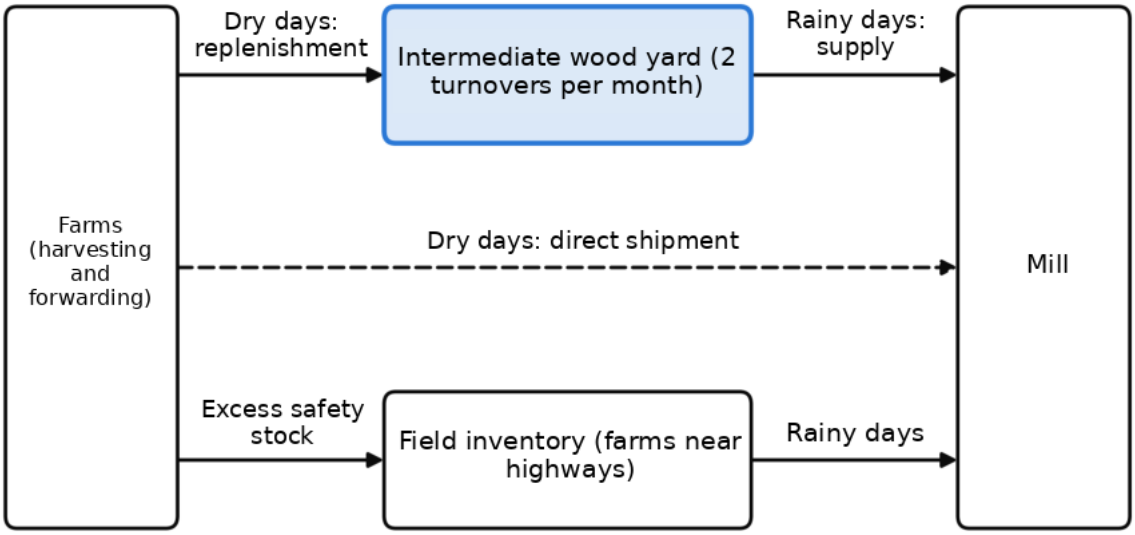
stream: on dry days, the wood goes directly to the factory or is taken to the yard; on rainy days, the factory is supplied by the yard and, when its capacity is insufficient, by the stock that remains in the field.

Figure 2 – Proposed supply flow with the intermediate yard



Source: drawn up by the author (2026).

3.2 Data collection

The data were obtained from possible scenarios of the company's supply planning for 2027 and from internal cost estimates. They were collected and adapted: the monthly volume of timber to be delivered to the factory, the number of rainy and dry days per month, the load capacity of the vehicles, the number of journeys, costs per kilometre of road and the costs of installation and operation of the yard.

In addition, information obtained from a technical visit to the company's forest operations and industrial unit in April 2026 which included the areas of strategic planning, micro-planning, roads, loading, monitoring centre and wood yard was used.

3.3 Model parameters

The total volume considered in this study for the year 2027 is 6,045,788 m³, transported in compositions with a load box of 65 m³, resulting in about 93,000 journeys per year, between 221 and 287 per day.

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The rainfall ratio for each month corresponds to the ratio between rainy days and total days of the month, ranging from 8% in July to 54% in January. The monthly safety stock is the volume that needs to be available for rainy days, according to Equation 1:

$$ES_m = V_m \times DC_m / D_m \quad (1)$$

where ESm is the safety stock for month m, in m³; Vm is the volume to be delivered to the mill, in m³; DCm is the number of rainy days; and Dm is the number of days in the month. Summing the twelve months gives annual safety stock of 1,693,190 m³.

Road costs were calculated per kilometer of internal access road, with a width of 4 m, and adapted for this study. Direct shipment costs, meaning road preparation so that trucks can remove timber from farms on rainy days, total BRL 87,105/km and comprise two components. The first, BRL 37,949/km, corresponds to the basic road without crushed stone, which is required with or without the yard. The second, BRL 49,156/km, corresponds to placing crushed stone, which is needed only when rainy-day stock remains in the field. Under the current model, maintaining safety stock requires approximately 376 km of gravel roads, equivalent to about 4,500 m³ of safety stock per kilometer. Costs can therefore be expressed per cubic meter of safety stock: BRL 8.43 for the basic road, BRL 10.92 for crushed-stone placement, and BRL 19.36 for total direct shipment costs. Since the basic road remains necessary, yard savings correspond only to the crushed stone that no longer needs to be placed. Wider external access roads were excluded because they remain necessary for truck passage.

The yard is emptied on rainy days and refilled on dry days, called in this work supply windows. Each complete cycle of emptying and refilling is called a turn, and the yard's monthly moving capacity corresponds to the physical capacity multiplied by the number of turns.

The number of turnovers was fixed at two per month for all scenarios. After each rainy period, the soil must be allowed to dry so that trucks can enter farms without becoming stuck or requiring emergency road maintenance. A third monthly replenishment would shorten this interval and require more machine and truck operating hours, as well as crushed stone to ensure access for yard replenishment, contrary to the study's aim. It would also increase fuel consumption and reduce productivity, compromising supply to the mill. Thus, in months when safety stock exceeds twice the yard's physical capacity, the surplus remains as field stock. This stock should be planned on farms near paved highways, which the company already has available for such situations, so that trucks travel shorter internal road sections on rainy days, reducing the risk of becoming stuck and trafficability problems.

Wood handling in the yard is performed by grapple-equipped forest log loaders, referred to in this study as cranes. Their productivity was calculated from operating cycle time using internal study data. Each cycle, comprising picking logs from the pile, swinging while

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loaded, unloading, and auxiliary movements, takes 63.2 seconds, corresponding to approximately 57 cycles per hour. For logs 7 m long with an average diameter of 102 mm, each grapple load moves about 3.64 m³. Overall equipment effectiveness (OEE) is 81%, resulting from 90% mechanical availability and 90% operating efficiency.

The internal study applies the OEE four times throughout the calculation, on the number of cycles and on working hours, resulting in 65,205 m³/month per machine, a conservative estimate. At the opposite extreme, applying the OEE once over the theoretical capacity would result in 122,695 m³/month, an optimistic estimate. In this work, an intermediate position was adopted: OEE was applied once on the number of cycles, which goes up to 46.1 cycles per hour, and once on working hours, which go up to 19.44 effective hours per day. Productivity was achieved at 168 m³/h, 3,265 m³/day and 99,383 m³/month per machine. Conservative and optimistic estimates were assessed in the sensitivity analysis.

3.4 Model construction

The model was built on an electronic spreadsheet. For each month, the volume absorbed by the yard is the lowest value between safety stock and handling capacity (Equation 2); the remainder remains in the field (Equation 3):

$$VP_m = \min(ES_m; g \times C) \quad (2)$$

$$VC_m = ES_m - VP_m \quad (3)$$

where VPm is the volume absorbed by the yard in a month, in m³; C is the physical yard capacity, in m³; g is the number of monthly turnovers; and VCm is the volume remaining as field stock, in m³.

The required yard area was calculated from its physical capacity. The area occupied by log piles (Equation 4) accounts for the wood stacking factor and log length; total area (Equation 5) adds space for truck circulation and maneuvering so that piles occupy 70% of the yard, with the remaining 30% available for those movements:

$$A_p = C \times f / L \quad (4)$$

$$A_t = A_p / 0{,}7 \quad (5)$$

where Ap is the log pile area, in m²; f is the wood stacking factor, 1.97; L is log length, 7 m; and At is the total yard area, in m².

The number of cranes required each month was obtained by dividing monthly handling volume by the productivity of one machine (Equation 6). Handling volume is twice the volume absorbed by the yard because each cubic meter is unloaded on arrival and loaded on

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departure. The result was always rounded up to the next integer. As calculated requirements are rarely exact integers, this rule ensures that the fleet covers all monthly handling and provides spare capacity: when one machine stops for maintenance, the others take over with less overload and fewer truck queues. The fleet for each scenario corresponds to the highest monthly requirement.

$$G_m = \lceil 2 \times VP_m / Pg \rceil \quad (6)$$

where Gm is the number of cranes in month m, ⌈ ⌉ denotes rounding up to the next integer, and Pg is the monthly productivity of one crane, 99,383 m³/month.

The model was verified by a daily calculation of the most critical month, January. On rainy days, the plant's supply of about 15,000 m³/day was divided between the yard and the field stock; on dry days, the factory was supplied by the dry areas, and the yard was replenished. The calculation confirmed that the yard balance remains between zero and its physical capacity throughout the month.

The sizing decision was formulated as an optimization problem. The decision variable is physical yard capacity, C, and the objective is to maximize annual net savings (Equation 7), corresponding to the crushed-stone placement costs avoided by the volume absorbed in the yard, less annual operating expenditure:

$$\text{Max. } E = \left(\Sigma\, VP_m \right) \times cc - OPEX, \text{ with } m = 1, \ldots, 12 \quad (7)$$

where E is annual net savings, in Brazilian reais; cc is the cost of crushed-stone placement per cubic meter of safety stock, BRL 10.92/m³; and OPEX is the annual yard operating cost, in Brazilian reais, which depends on the crane fleet. The objective function is subject to the following constraints:

a) the volume absorbed by the yard in each month shall not exceed the safety stock of the month: $VPm \leq ESm$;
b) the absorbed volume shall not exceed the handling capacity of the yard: $VPm \leq g \times C$;
c) the number of turns is fixed at two per month: $g = 2$;
d) the crane fleet shall meet monthly movements in accordance with Equation 6;
e) physical capacity is selected from the evaluated alternatives: $C \in \{30{,}000; 40{,}000; 50{,}000; 60{,}000\}$ m³.

Since capacity assumes few possible values, the problem was solved by enumeration, calculating the objective function for each alternative. The return on investment was measured by the simple payback (Equation 8):

$$\text{Payback} = CAPEX / E \quad (8)$$

where CAPEX is the yard implementation investment, in Brazilian reais.

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3.5 Scenarios and sensitivity analysis

Four physical yard capacity scenarios were calculated: 30,000, 40,000, 50,000, and 60,000 m³. Costs for each scenario were calculated from the company's unit implementation and operating costs for a yard with three machine sets. Items dependent on the number of machines, such as equipment, maintenance, fuel, and crane operators, were adjusted in proportion to each scenario's fleet. Other items, such as the weighbridge, infrastructure, information technology, logistics operators, and land rental, were held constant. In the sensitivity analysis, crushed-stone costs, OPEX, CAPEX, and safety stock were varied by ±20%, and optimistic and conservative crane productivity estimates were tested.

4. Results

4.1 Comparison of capacity scenarios

The volume absorbed increases with the capacity of the yard but at a decreasing rate (Table 1). Moving from 30,000 to 40,000 m³ adds 180,667 m³/year absorbed; from 40,000 to 50,000 m³, 170,169 m³; and from 50,000 to 60,000 m³, 131,783 m³. This is because in the dry months, the safety stock is already less than the carrying capacity, and the additional space becomes idle.

Table 1 – Results by yard capacity scenario

Physical capacity (m³)	Maximum throughput (m³/month)	Volume absorbed (m³/year)	Share of safety stock (%)	Field stock (m³/year)	Yard utilization (%)
30.000	60.000	704.265	41,6	988.925	97,8
40.000	80.000	884.932	52,3	808.258	92,2
50.000	100.000	1.055.101	62,3	638.089	87,9
60.000	120.000	1.186.884	70,1	506.306	82,4

Source: drawn up by the author (2026).

The area and crane fleet for each scenario are presented in Table 2. The 30,000 and 40,000 m³ yards operate with 2 cranes, while the 50,000 and 60,000 m³ yards use 3. For the 50,000 m³ yard, calculated peak requirements are 2.01 cranes, leaving almost one entire machine available; for the 60,000 m³ yard, the requirement is 2.41 cranes, still leaving approximately 0.6 machines available.

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Table 2 – Physical size of the yard by scenario

Physical capacity (m³)	Log pile area (m²)	Total area (m²)	Calculated peak crane requirement	Crane fleet
30.000	8.443	12.061	1,21	2
40.000	11.257	16.082	1,61	2
50.000	14.071	20.102	2,01	3
60.000	16.886	24.122	2,41	3

Source: drawn up by the author (2026).

4.2 Economic results of the scenarios

All scenarios are economically viable (Table 3 and Figure 3). The 50,000 and 60,000 m³ yards have the same investment and operating expenditure because they use the same fleet of 3 cranes. However, the 60,000 m³ yard absorbs an additional 131,783 m³ per year and therefore achieves the largest net savings, BRL 7.33 million annually, compared with BRL 5.89 million for the 50,000 m³ yard. The 40,000 m³ yard has the same payback as the 60,000 m³ yard, 0.71 years, but absorbs less volume and generates BRL 1.72 million less in annual savings.

Table 3 – Economic outcome by scenario

Physical capacity (m³)	Crane fleet	CAPEX (BRL thousand)	OPEX (BRL thousand/year)	Avoided crushed-stone cost (BRL thousand/year)	Net savings (BRL thousand/year)	Payback (years)
30.000	2	3.994	4.061	7.693	3.632	1,10
40.000	2	3.994	4.061	9.667	5.605	0,71
50.000	3	5.194	5.635	11.525	5.891	0,88
60.000	3	5.194	5.635	12.965	7.330	0,71

Source: drawn up by the author from adapted company data (2026).

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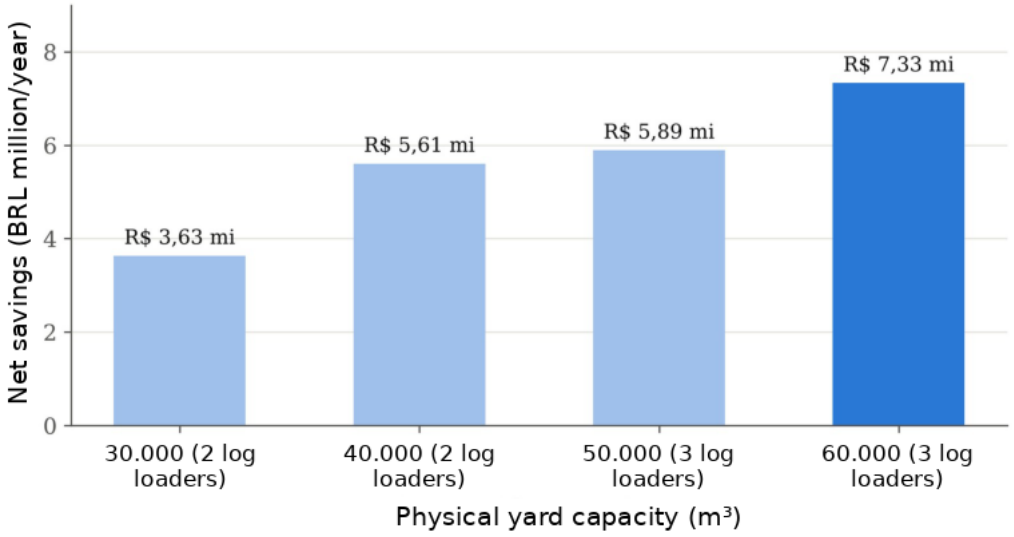
Figure 3 – Annual net savings by physical capacity of the yard



Source: drawn up by the author (2026).

As net savings are the model's objective function, the 60,000 m³ yard was selected as the recommended alternative, and its results are detailed below.

4.3 Monthly safety stock distribution in the recommended scenario

In the 60,000 m³ yard, the volume remaining in the field drops from 1,693,190 m³ to 506,306 m³ per year (Table 4). From April to September, the yard takes care of all the safety stock on its own. From October to March, the safety stock exceeds the handling capacity of 120,000 m³/month, and the surplus continues on farms, reaching 121,817 m³ in January.

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Table 4 – Monthly distribution of safety stock in the yard of 60,000 m³

Month	Volume delivered (m³)	Rainfall (%)	Safety stock (m³)	Absorbed by yard (m³)	Remaining in field (m³)	Number of cranes
Jan	451.948	54	241.817	120.000	121.817	3
Feb	411.143	49	203.110	120.000	83.110	3
Mar	445.245	36	161.383	120.000	41.383	3
Apr	505.206	22	110.108	110.108	0	3
May	546.152	17	90.169	90.169	0	2
Jun	552.293	11	60.667	60.667	0	2
Jul	569.579	8	45.719	45.719	0	1
Aug	577.652	10	58.546	58.546	0	2
Sep	543.141	19	101.675	101.675	0	3
Oct	489.306	38	185.269	120.000	65.269	3
Nov	472.127	41	194.695	120.000	74.695	3
Dec	481.996	50	240.032	120.000	120.032	3
Total	6.045.788	30	1.693.190	1.186.884	506.306	–

Source: drawn up by the author from adapted company data (2026).

The 3 cranes are needed from September to April. From May to August, 2 are sufficient, and in July only 1 is required. Machines available during this period can undergo scheduled preventive maintenance or be temporarily assigned to other company operations, such as field loading, increasing fleet utilization throughout the year.

4.4 Investment costs and economic results of the recommended yard

The investment to implement the 60,000 m³ yard is R$ 5.19 million, of which 69% corresponds to handling equipment (Table 5). The annual operating cost is R$ 5.63 million, with equipment maintenance accounting for 48% (Table 6).

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Table 5 – Investment for the installation (CAPEX) of the 60,000 m³ yard

Category	Items	Value (BRL thousand)	Share (%)
Equipment	3 forest crane sets (base machine and grapple crane)	3.599	69
Infrastructure	Truck weighbridge and semi-trailer	1.243	24
Weighbridge installation	Labor materials and painting	300	6
Information technology	Computers printer and network infrastructure	52	1
Total		5.194	100

Source: drawn up by the author from adapted company data (2026).

Table 6 – Annual operating cost (OPEX) of the 60,000 m³ yard

Category	Items	Value (BRL thousand/year)	Share (%)
Maintenance	Crane maintenance	2.685	48
Labor	11 crane operators and 4 logistics operators	1.528	27
Fuel	Cranes and support vehicle	1.017	18
Other	Land rental meals internet and transport	405	7
Total		5.635	100

Source: drawn up by the author from adapted company data (2026).

Table 7 compares annual costs under the current model, involving direct shipment from farms to the mill, with those under the yard model. Under the current model, direct shipment costs total BRL 32.77 million per year, comprising BRL 14.28 million for basic roads and BRL 18.50 million for crushed-stone placement. With the yard, basic roads remain necessary, but crushed-stone costs fall to BRL 5.53 million. Adding yard operating expenditure gives a total of BRL 25.44 million per year. Net savings are BRL 7.33 million annually, and the investment pays back in 0.71 years, approximately 8.5 months.

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Table 7 – Comparison between the current model and the 60,000 m³ yard model

Indicator	Current model (direct shipment)	Model with yard
Field safety stock (m³/year)	1.693.190	506.306
Yard safety stock (m³/year)	0	1.186.884
Basic road without crushed stone (BRL thousand/year)	14.279	14.279
Crushed-stone placement (BRL thousand/year)	18.496	5.531
Yard OPEX (BRL thousand/year)	–	5.635
Total annual cost (BRL thousand/year)	32.774	25.444
Net savings (BRL thousand/year)	–	7.330
Yard CAPEX (BRL thousand)	–	5.194
Simple payback (years)	–	0,71

Source: drawn up by the author from adapted company data (2026).

Per cubic meter, yard operating costs are BRL 4.75, less than half the avoided crushed-stone cost of BRL 10.92. Net savings equal BRL 6.18 per cubic meter stored in the yard.

4.5 Sensitivity analysis

The yard remains viable under all tested variations (Table 8 and Figure 4). Results are most sensitive to crushed-stone costs: a 20% reduction lowers net savings to BRL 4.74 million per year, and the project would cease to be viable only if this cost fell by about 57%, to below BRL 4.75 per cubic meter. OPEX and safety stock, which reflects the number of rainy days, have smaller effects. Increased safety stock has a limited effect because the yard already reaches its handling capacity in the rainiest months and surplus stock remains in the field. CAPEX does not change annual savings, only payback, which remains below one year. Under the optimistic productivity estimate, the fleet decreases to 2 cranes and net savings rise to BRL 8.90 million annually; under the conservative internal-study estimate, the fleet increases to 4 cranes and net savings fall to BRL 5.76 million annually, with payback in just over one year.

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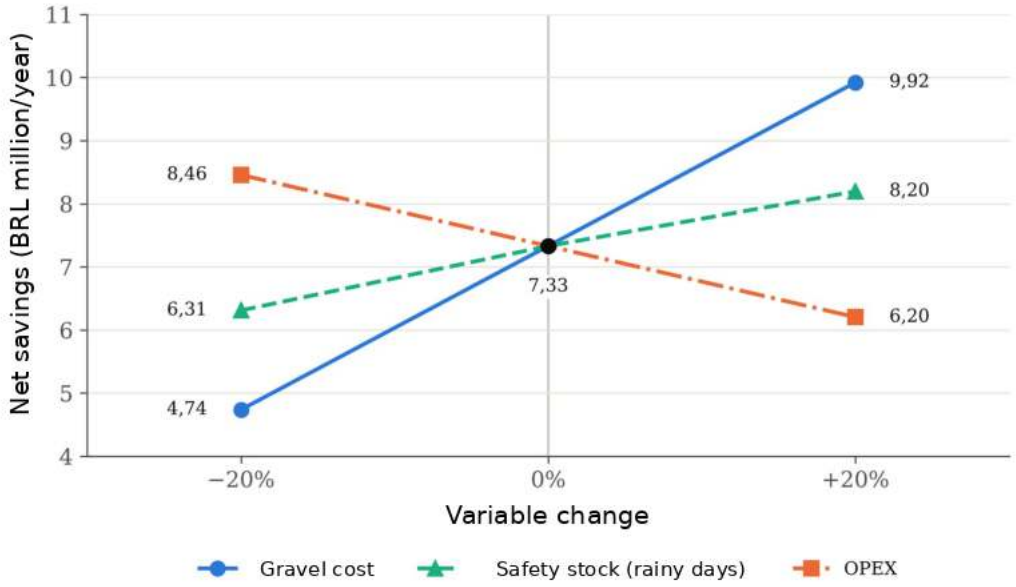
Table 8 – Sensitivity of the net savings and payback (60,000 m³)

Variation	Net savings (BRL thousand/year)	Payback (years)
Recommended scenario	7.330	0,71
Crushed-stone cost −20%	4.737	1,10
Crushed-stone cost +20%	9.923	0,52
Safety stock −20%	6.310	0,82
Safety stock +20%	8.196	0,63
OPEX -20%	8.457	0,61
OPEX +20%	6.203	0,84
CapEX -20%	7.330	0,57
CAPEX +20%	7.330	0,85
Optimistic crane productivity (2 cranes)	8.904	0,45
Conservative crane productivity (4 cranes)	5.756	1,11

Source: drawn up by the author (2026).

Figure 4 – Sensitivity of the net savings to the main variables (60,000 m³)



Source: drawn up by the author (2026).

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5. Discussion

The results confirm that an intermediate yard is an economically viable alternative for reducing dependence on gravel roads during rainy periods. With a capacity of 60,000 m³ and two monthly turnovers, the yard concentrates 70% of safety stock and generates annual net savings of BRL 7.33 million, with investment payback in approximately eight and a half months. This finding is consistent with the use of intermediate terminals in Finland and Sweden to ensure supply during periods of poor trafficability (VÄÄTÄINEN et al., 2021).

Seixas and Widmer (1993), by contrast, found intermediate yards unviable because of additional loading and unloading costs. The difference lies in what each study compares: their study assessed yards solely as transport transfer points; here, the yard replaces an infrastructure cost, crushed-stone placement on internal roads, which is more than twice the yard's operating cost per cubic meter. This reinforces Ballou's (2006) view that logistics decisions should consider total system costs.

The logic of the intermediate yard is already adopted in the factory itself, whose main yard contains more than 270,000 m³ of wood and has alternative yards used as support during operational stops and rainy periods. The proposal for this work brings this strategy closer to harvest areas.

The scenario comparison shows that yard costs depend on the crane fleet, determined by the volume handled in the yard. This volume, in turn, depends on physical capacity and each month's safety stock, which reflects the rainy days considered in planning. Costs therefore increase in steps rather than continuously with capacity. Because the 50,000 and 60,000 m³ yards use the same fleet of 3 cranes, the 60,000 m³ yard makes better use of this fleet and absorbs more volume at the same operating cost. The 30,000 and 40,000 m³ yards require less investment but leave more stock in the field and therefore more roads requiring gravel surfacing.

The rule of always rounding up the number of cranes was adopted because calculated requirements are rarely an exact integer and yard operation cannot depend on machines working at their limit. For the 60,000 m³ yard, peak demand is 2.41 cranes; with 3 machines, if one stops for maintenance, the other two still cover approximately 83% of peak handling, and all handling in the remaining months. In months with fewer rainy days, this spare capacity also allows machines to be assigned to other company operations. It also reduces machine overload and truck queues, a concern that helps explain the conservative internal-study productivity calculation, which applies OEE more than once to account for possible downtime. Because the fleet depends on handled volume, which varies with forecast rainy days, the size and costs of each scenario should be recalculated whenever rainfall planning is updated, and confirmed through specific quotations before a final decision.

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The sensitivity analysis also shows that results are robust to the adopted assumptions. Even with crushed-stone costs 20% lower, payback is only slightly over one year, and with OPEX 20% higher it remains below one year. Crane productivity was estimated at an intermediate level between the company's internal study, which applies OEE four times, and a calculation applying OEE only once; even under the most conservative estimate, requiring 4 cranes, the yard pays back in just over one year. The calculation includes only avoided crushed stone on internal access roads: basic roads remain necessary, as do external access roads, to ensure trafficability and mill supply. In addition, because surplus stock can be concentrated on farms near paved highways, the length of roads requiring gravel surfacing may be even smaller than assumed, indicating that estimated savings are conservative.

In the company, the safety stock is defined in long-term planning with a horizon of up to about 21 years, deployed in annual plans passed on to the PCP. A tactical planning, with a significantly smaller horizon, is in development. The proposed model fits into this tactical level as it supports an infrastructure decision affecting several years of supply.

The study has limitations. The model works on monthly averages of rainy days, without taking into account the variability between years; does not include the cost of additional transportation between farm, yard and factory nor the opportunity cost of capital; and does not assess the loss of quality of wood stored for longer, an effect observed by Eufrade-Junior et al. (2021) in the rainy season.

6. Final considerations

This study developed a model for sizing an intermediate wood yard to reduce gravel surfacing costs on internal roads in a pulp forestry company. In answer to the research question, a yard with a physical capacity of 60,000 m³ and two monthly turnovers absorbs 70% of annual safety stock, maintains mill supply, and reduces field stock from 1.69 million to 0.51 million m³. This requires a total yard area of approximately 24,100 m² and a fleet of 3 cranes.

The investment of R$ 5.19 million reduces the annual direct shipping cost from R$ 32.77 million to R$ 25.44 million, a net savings of R$ 7.33 million per year, and is paid in about 8.5 months. The comparison between scenarios showed that the number of cranes defines the cost of each yard size and that 60,000 m³ maximizes net savings by making better use of the three-crane fleet, which also provides spare time for maintenance. The sensitivity analysis indicated that the project remains feasible even with 20% variations in the main variables and the most conservative crane productivity estimate.

For the company, the model serves as a decision support tool, easy to update with each new annual planning. For Production Engineering, the study shows how scenario modeling can integrate logistics, inventory management and infrastructure into a single decision.

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Future work should include rainfall variability through stochastic models; measure actual yard crane productivity in the field; confirm estimated costs for each yard size through quotations; incorporate additional transport costs and the time value of money using NPV and IRR; and optimize yard location relative to farms and the mill.

Declaration of artificial intelligence use

In accordance with the UFMS Artificial Intelligence Policy (Resolution No. 455-COUN/UFMS, of December 1, 2025), this work declares the use of the generative artificial intelligence tool Claude, model Opus 5.5, developed by Anthropic, in the following stages:

a) literature research: assistance in searching for articles on the subject, subsequently checked by the author in the original sources;
b) writing: assistance in organizing sections and editing preliminary texts, subsequently revised and rewritten by the author;
c) calculations: assistance in organizing and modifying the data for calculating scenarios and sensitivity analysis, checked by the author.

The research problem, intermediate yard model, data, and assumptions were developed by the author during her internship at the company studied. All content was reviewed, validated, and rewritten by the author, who assumes full responsibility for the text, data, and conclusions. The tool is not considered a coauthor of this work.

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