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DÉFIS OPÉRATIONNELS ET COÛTS D'EXPLOITATION / RECHERCHE

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What are the operational challenges and costs for forestry forwarders under different site conditions in southern Bahia, Northeastern Brazil?

Photo 1.
Forestry forwarder used to extract round timber from a eucalyptus plantation in southern Bahia, Northeastern Brazil.
Photo C. F. Lima.

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RÉSUMÉ

Quels sont les défis opérationnels et les coûts pour les porteurs-chargeurs forestiers dans différentes conditions de terrain dans le sud de Bahia, au nord-est du Brésil ?

Le secteur brésilien des forêts plantées joue un rôle essentiel dans la durabilité économique et environnementale, favorisant la mécanisation pour répondre aux demandes du marché. Cependant, les études portant sur les performances opérationnelles dans la région nord-est restent rares, en particulier dans des conditions de terrain et de peuplement variables. De plus, il existe un manque de modèles prédictifs reliant la productivité des porteurs-chargeurs aux coûts opérationnels et aux stratégies d'extraction adaptées à la variabilité locale des sites. Il convient de noter que l'extraction forestière au Brésil est confrontée à des défis en raison de la variabilité des conditions édapho-climatiques, qui ont un impact sur la productivité des porteurs-chargeurs et les coûts opérationnels. Cette étude visait à évaluer comment des facteurs opérationnels spécifiques (tels que la distance d'extraction, la capacité de charge du porteur-chargeur, la productivité forestière et la répartition du temps dans le cycle opérationnel de la machine) influencent l'efficacité et les coûts de l'extraction du bois. Les données de terrain ont été collectées dans le sud de Bahia, une zone stratégique pour l'industrie de la pâte à papier et du papier, dans des peuplements présentant des niveaux de productivité et des rotations forestières distincts. Des études sur le temps et les mouvements, une régression linéaire, et une analyse des coûts ont révélé que les modèles prédictifs expliquaient jusqu'à 92 % de la productivité des porteurs-chargeurs. Une forte corrélation inverse a été observée entre la productivité et la distance d'extraction. Ce résultat souligne l'importance de réduire au minimum les longs trajets afin de diminuer les coûts. La productivité était directement proportionnelle au rendement forestier, le processus de chargement des porteurs-chargeurs représentant jusqu'à 42 % du cycle opérationnel. L'utilisation de porteurs-chargeurs de plus grande capacité a permis d'optimiser l'extraction, avec une moyenne de 21 m³ par trajet. L'analyse des coûts a montré une augmentation de 26 % du coût par mètre cube avec une baisse du rendement forestier et une augmentation de 61 % avec des distances d'extraction plus longues. Ces résultats définissent les paramètres opérationnels optimaux pour le sud de Bahia, dans le nord-est du Brésil, en mettant l'accent sur la rentabilité et l'amélioration des performances.

Mots-clés : opérations forestières, étude des temps de cycle de travail, extraction du bois, productivité des machines forestières, Brésil.

ABSTRACT

What are the operational challenges and costs for forestry forwarders under different site conditions in Southern Bahia, Northeastern Brazil?

The Brazilian planted forest sector plays a vital role in economic and environmental sustainability, favouring mechanisation to meet market demands. However, studies addressing operational performance in the northeastern region remain scarce, particularly under varying site and stand conditions. Moreover, there is a lack of predictive models that link forestry forwarder productivity to operational costs and extraction strategies adapted to local site variability. It is noteworthy that forest extraction in Brazil faces challenges due to the variability of edaphoclimatic conditions, impacting forestry forwarder productivity and operational costs. This study aimed to evaluate how specific operational factors (such as extraction distance, forestry forwarder load capacity, forest productivity, and time allocation within the machine's operational cycle) influence the efficiency and costs of timber extraction. Field data were collected in southern Bahia, a strategic area for the pulp and paper industry, across stands with distinct productivity levels and forest rotations. Time and motion studies, linear regression, and cost analysis revealed that predictive models explained up to 92% of forestry forwarder productivity. A strong inverse correlation was found between productivity and extraction distance. This result highlights the importance of minimising long hauls to reduce costs. Productivity was directly proportional to forest yield, with the forestry forwarder loading process representing up to 42% of the operational cycle. The use of higher-capacity forestry forwarders has optimised extraction, with an average of 21 m³ per trip. Cost analysis showed a 26% increase in cost per cubic metre with decreased forest yield and a 61% increase with longer extraction distances. These findings define optimal operational parameters for Southern Bahia, Northeastern Brazil, emphasising cost-efficiency and performance improvements.

Keywords: forestry operations, work cycle time study, timber extraction, productivity of forestry machines, Brazil.

RESUMEN

¿Cuáles son los desafíos operativos y los costes para las procesadoras forestales en diferentes condiciones de terreno en el sur de Bahía, en el noreste de Brasil?

El sector forestal brasileño juega un papel fundamental en la sostenibilidad económica y medioambiental, favoreciendo la mecanización para satisfacer las demandas del mercado. Sin embargo, los estudios que abordan el rendimiento operativo en la región noreste siguen siendo escasos, especialmente en condiciones de terreno y masas forestales variables. Además, faltan modelos predictivos que relacionen la productividad de las procesadoras con los costes operativos y las estrategias de extracción adaptadas a la variabilidad local del terreno. Cabe destacar que la extracción forestal en Brasil se enfrenta a desafíos debido a la variabilidad de las condiciones edafoclimáticas, lo que repercute en la productividad de las procesadoras y en los costes operativos. El objetivo de este estudio era evaluar cómo influyen factores operativos específicos (como la distancia de extracción, la capacidad de carga de las procesadoras, la productividad forestal y la distribución del tiempo dentro del ciclo operativo de la máquina) en la eficiencia y los costes de la extracción de madera. Los datos de campo se recopilaron en el sur de Bahía, una zona estratégica para la industria de la pulpa y el papel, en rodales con distintos niveles de productividad y rotaciones forestales. Los estudios de tiempo y movimiento, la regresión lineal y el análisis de costes revelaron que los modelos predictivos explicaban hasta el 92 % de la productividad de las procesadoras forestales. Se encontró una fuerte correlación inversa entre la productividad y la distancia de extracción. Este resultado destaca la importancia de minimizar los transportes largos para reducir los costes. La productividad era directamente proporcional al rendimiento forestal, ya que el proceso de carga de las procesadoras representaba hasta el 42 % del ciclo operativo. El uso de procesadoras de mayor capacidad permitió optimizar la extracción, con una media de 21 m³ por trayecto. El análisis de costes mostró un aumento del 26 % en el coste por metro cúbico con una disminución del rendimiento forestal y un aumento del 61 % con distancias de extracción más largas. Estos resultados definen los parámetros operativos óptimos para el sur de Bahía, en el noreste de Brasil, haciendo hincapié en la rentabilidad y la mejora del rendimiento.

Palabras clave: operaciones forestales, estudio del tiempo de ciclo de trabajo, extracción de madera, productividad de máquinas forestales, Brasil.

Introduction

The Brazilian planted forest sector is a key driver of the country's economic and environmental sustainability, covering 9.94 million hectares of tree plantations. Of this total, 76% is allocated to eucalyptus plantations, which are primarily used for pulp and paper production but also support energy generation, charcoal, and wood panel industries. In 2022, the sector contributed 6.3% to Brazil's Gross Domestic Product (GDP), generating a gross revenue of BRL 260 billion and producing 25 million tonnes of cellulose (IBÁ 2023). Beyond its economic significance, the sector stands out for its competitiveness in the international market, positioning Brazil as a leading global producer and exporter of pulp.

The increasing demand for forest-based products has driven the mechanisation of harvesting and extraction operations, aiming to enhance productivity and reduce operational costs. However, the variability in edaphoclimatic conditions across different regions of the country significantly affects machine performance in these processes (Lima et al. 2024a). In this context, edaphoclimatic conditions — encompassing soil texture, compaction, moisture levels, slope, and climatic variables such as rainfall and temperature — directly influence the traction, stability, travel speed, and fuel efficiency of forestry forwarders, commonly named forwarder, thereby impacting overall productivity and extraction costs (Labelle et al. 2022; Lima et al. 2025; Ferreira et al. 2025).

While most studies on forestry mechanisation in Brazil focus on the South and Southeast regions, there is a lack of research addressing the operational challenges faced in the Northeast. This gap limits the applicability of predictive models for productivity and costs, as factors such as extraction distance, soil characteristics, vegetation density, and forest yield may influence forwarder performance differently depending on the operational context.

The favourable edaphoclimatic conditions of the Northeastern Brazilian region, including a predominantly tropical climate with distinct wet and dry seasons, well-drained sandy to loamy soils that facilitate machine mobility, moderate topography characterised by flat to gently rolling terrain, and extensive eucalyptus plantations with short rotation cycles adapted to these conditions, drive the mechanisation of forestry operations, emphasising increased productivity and reduced production costs, particularly in technical, operational, and economic contexts (De Assis Costa Ferreira et al. 2024).

This approach is crucial for generating precise data that supports the planning and decision-making processes in tree plantations (Lima et al. 2023). Diligent planning of harvesting operations is essential for minimising operational and production costs, ensuring a consistent supply of wood to processing facilities, and maintaining the operational integrity of machinery in the field (De Souza Gomes et al. 2021; De Assis Costa Ferreira et al. 2023). The integration of technological advancements in harvesting machinery is vital for enhancing the feasibility of commercial forestry production and improving overall system efficiency (Lima et al. 2019).

In Brazil, the cut-to-length system is the predominant method used in timber harvesting for pulpwood production (Munis et al. 2023a). In this system, trees are processed into logs up to six meters long, which are then transported by a self-loading machine known as a forwarder (Bont et al. 2022). The forwarder removes the logs from within the harvesting area and places them at designated roadside points. This operation is essential for ensuring efficiency and continuity in the supply chain.

The productivity of the forwarder is affected by several operational and environmental factors, including average volume per tree, extraction distance, and the efficiency of loading and unloading activities. The spatial arrangement of woodpiles and the interaction between operator and machine also play an important role in overall performance (Schettino et al. 2022; Lima et al. 2024b).

Variations in performance are often associated with specific practices and configurations adopted by forestry companies (Cadei et al. 2020). However, current studies provide limited analysis of how forest productivity and the conditions of the load box influence the efficiency of forwarder operations. This highlights the need for more detailed and regionally adapted models to support improved decision-making in timber extraction.

Certain variables affecting forwarder productivity can be managed or altered by forest operators, such as planting spacing, harvesting system configuration, number of logs per trip, and load volume (Proto et al. 2017; Cadei et al. 2020). These variables are tied to operational decision-making and can be optimised to enhance productivity, reduce costs, and improve machine allocation (Lima et al. 2025). In contrast, factors like terrain slope, soil type, and extraction distance are site-specific and non-modifiable, as they are intrinsic to the physical and environmental characteristics of the forest site (Ferreira et al. 2025). Despite their fixed nature, these variables play a crucial role in strategic planning and resource allocation. Understanding the limitations imposed by slope or distance allows managers to adjust work cycles, choose appropriate machinery, and design more efficient extraction layouts.

Several studies emphasise the significant impact of terrain slope and extraction distance on operational efficiency. For instance, Marcu et al. (2024) and Stankić et al. (2012) demonstrated that increased slope and unfavourable trail conditions reduce productivity by increasing cycle times. Similarly, Cabral et al. (2020) and Malinovski et al. (2006) identified extraction distances greater than 150 m as a threshold beyond which forwarder productivity decreases sharply. More recent findings by Ezzati et al. (2021), using Monte Carlo simulation in Eucalyptus plantations, show that forwarder productivity on undulating or sloped terrain is nearly 30% lower compared to flat ground, with operational costs per cubic meter increasing significantly. Additionally, Palander (2025) highlights that fuel consumption varies according to slope, with cut-to-length harvesting on sloped terrain resulting in up to 15% higher fuel use than on flat areas.

Therefore, it is essential to incorporate both modifiable and non-modifiable variables into operational models to enable realistic performance forecasts. This approach allows forest managers to optimise aspects under their control while adapting their strategies to the environmental constraints of each site, ultimately improving the sustainability and efficiency of forest extraction operations.

Studying timber extraction is vital for understanding the factors that influence productivity and costs in forestry operations, especially given the significant financial implications of forest harvesting. This process represents a substantial portion of the total cost of wood delivered to processing facilities (Dvořák et al. 2021; Miyajima et al. 2021; Rocha et al. 2022; Stoilov et al. 2023). While extraction can be costly, it is affected by various variables that directly impact machine productivity and operational expenses (Shadbahr et al. 2021). Thus, in-depth analysis is essential for developing accurate planning tools to ensure a continuous and cost-effective supply of wood to consumer units.

This study is based on the premise that optimising wood extraction operations, specifically the operational cycle of forwarders, depends on an integrated analysis of the variables influencing both productivity and operational costs in southern Bahia, Northeastern Brazil. The research aims to test a series of hypotheses regarding the influence of factors such as extraction distance, forwarder load capacity, forest productivity, and a detailed examination of the machine's operational cycle to understand how these aspects interact to impact the efficiency and costs of forestry operations.

Given this scenario, the present study seeks to bridge this gap by analysing the key factors affecting forwarder productivity and operational costs in the Northeast region of Brazil. The research examines how variables such as extraction distance, machine load capacity, forest yield, and operational cycle dynamics interact to determine extraction efficiency. The research includes predictive models of machine productivity under various conditions, an analysis of load capacity during extraction, an in-depth study of the forwarder's operational cycles, and a comprehensive evaluation of the associated production costs.

Specifically, the study tests four central hypotheses: (i) that forest productivity, represented by the average tree volume (AVT), significantly influences forwarder productivity; (ii) that a detailed breakdown of the operational cycle identifies the stages consuming the most time and limiting efficiency; (iii) that machines with larger load-box capacity, even when similar in other technical specifications, offer improved operational viability; and (iv) that extraction costs vary as a function of both AVT and extraction distance. These analyses focus on the unique environmental and operational conditions of southern Bahia, Northeastern Brazil, characterised by steep terrain, high temperatures, and predominantly short-rotation eucalyptus plantations, which collectively impact the productivity and cost dynamics of timber extraction.

Materials and Methods

Study area

The study was conducted in a forestry company located in the northeastern region of Brazil, in the state of Bahia, between meridians 39°34'30" and 40°34'48" west of Greenwich and parallels 16°22'23" and 17°22'00" south of the Equator (figure 1). According to Köppen's climate classification, the region has a tropical rainforest climate (Af), with an

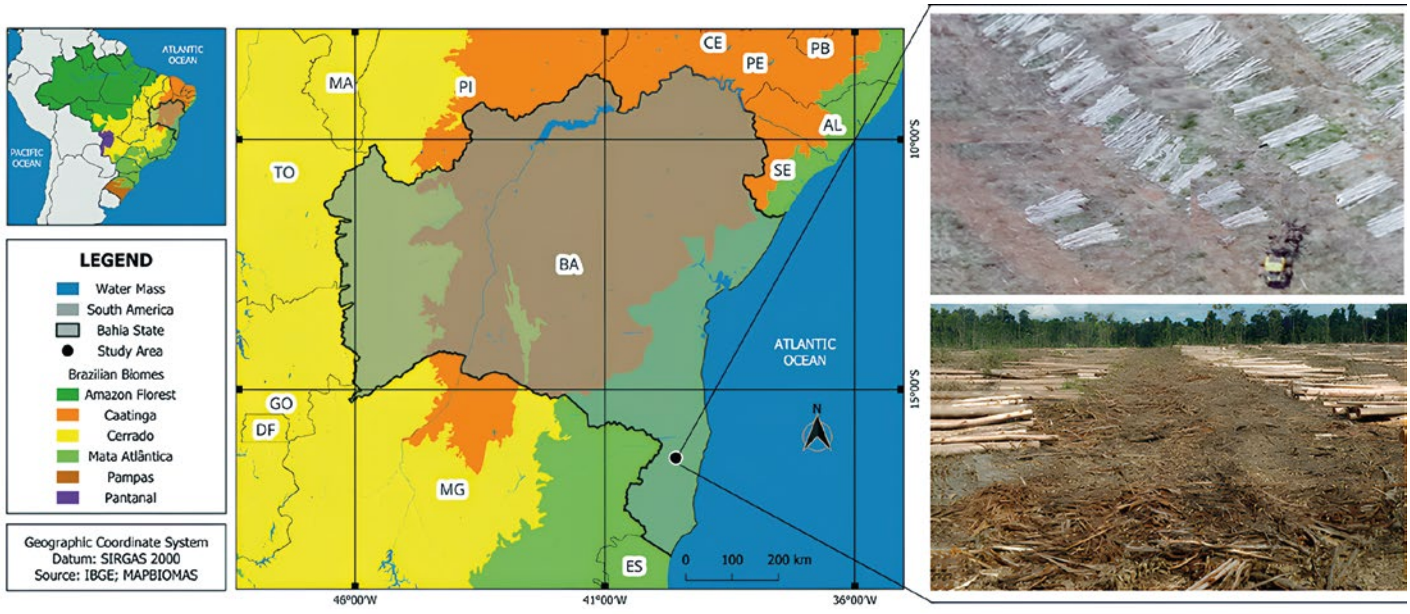

Figure 1.
Location of the study area for forest extraction in eucalyptus plantations in the state of Bahia (BA), Brazil. The map highlights Brazilian biomes (Amazon Forest, Caatinga, Cerrado, Atlantic Forest, Pampa, and Pantanal), with the study area situated within the Atlantic Forest biome.
The photos show aerial view (top photo) and ground level view (bottom photo) of the harvesting operations. Photos C. F. Lima.

average temperature of 23 °C and an annual precipitation of 1,256 mm (Alvares et al. 2013).

The studied mechanised wood harvesting operations were conducted on slopes of up to 25°, operating seven days a week in two eight-hour shifts, utilising the cut-to-length system. In this approach, trees are felled and processed within the stands into logs shorter than 6 m, which are then transported to roadside or intermediary storage areas (Masioli et al. 2024).

The forest stands in the study area are entirely composed of eucalyptus plantations, consisting of hybrid clones of *Eucalyptus* spp. managed in both first-rotation and second-rotation (coppice) plantations, with harvesting scheduled at six years of age in spacings of 4.0 × 3.0 m and 5.0 × 2.4 m.

Forest productivity data were obtained from pre-harvest inventory results conducted 30 to 60 days before the scheduled harvest. Field measurements for this study were carried out from August 2017 to January 2020, covering forest stands under varying edaphoclimatic conditions, which refer to the combined influence of soil characteristics (such as texture, compaction, and fertility) and climatic factors (such as temperature, rainfall, and humidity) that directly affect machine performance and timber extraction efficiency.

Machinery specifications and sampling procedures

In this study, the following machines were evaluated: a Ponsse Elephant wheeled forwarder and a Ponsse Elephant King wheeled forwarder, both used in wood extraction (table I, figure 2).

To establish the minimum number of cycles that would satisfy a maximum allowable sampling error of 5%, thus guaranteeing a confidence of 95% (equation 1), the methodology proposed by Barnes (1977) was adopted:

$$n \geq \frac{t * CV}{e^2} \quad \text{(equation 1)}$$

where n is the minimum number of cycles required; t is the t value, for the desired probability level and (n-1) degrees of freedom; CV is the variation coefficient t (%); e is the permissible sampling error at 95% probability.

The forest extraction operation was evaluated in eucalyptus stands with varying Average Volume per Tree (AVT) values ranging from 0.16 to 0.58 m^3 without bark (m^3 wb) and under management regimes (first and second rotation), considering the operational cycle elements as well as productivity and costs for each variable (table II).

Table I.
Description and specification of the evaluated forestry machines.

Number	Type	Tires	Brand	Model	Mass (t)	Load Capacity (t)	Traction (kN)
6	Forestry forwarder 8x8	Rigid Track	Ponsse	Elephant	22.8	18	220
2	Forestry forwarder 8x8	Rigid Track	Ponsse	Elephant King	23.7	20	240

Figure 2.
Two forestry forwarders models used in the study: Elephant (A), Elephant King (B).
Photos C. F. Lima.

Table II.
Summary of the evaluated variables.

AVT (m^3wb)	DBH (cm)	Height (m)	Plots	Calculated cycles	Collected cycles
0.16	15.50	21.70	5	63	375
0.20	16.00	24.00	5	75	375
0.31	18.20	26.90	5	80	375
0.36	19.90	30.50	5	54	375
0.46	21.30	31.70	5	69	375
0.58	22.90	35.50	5	76	375
Total			**30**	**417**	**2,250**

Forest productivity	AVT (m^3 wb)	Spacing (m)	Forest rotation	Calculated cycles	Collected cycles
Average	0.30 and 0.32	5.0 x 2.40	2nd	54	86
High	0.48	4.0 x 3.0	1st	49	64

AVT: average volume of tree without bark; DBH: diameter at breast height; Height (m) refers to the average height of *Eucalyptus* spp clones.

Study of production capacity and operational cycles

The machines studied operated in forest stands with slopes up to 25°. All operators had more than five years of experience exclusively operating forwarder models, and their productivity in cubic meters per hour met the company standards established for each harvesting block. None of the operators had recently undergone retraining courses or returned from any leave periods, such as vacations or medical absences, during the study. These factors ensured consistent operational conditions and minimised variability related to operator skills. A multimoment method was employed, with 15-second intervals through observation. Productivity was measured in cubic meters of wood per effective hour worked (m^3/he), following a methodology similar to that used by Lima et al. (2025).

To determine the time spent on each phase of wood extraction and loading activities, a time and motion study was conducted for each machine over a full work shift using the continuous timing method (Barnes, 1990). A digital stopwatch and data-recording form were used for data collection. The forwarder's operational cycle was divided into the following phases: 1) empty travel; 2) loading; 3) loaded travel; and 4) unloading.

Forwarder activities were recorded using video cameras installed both inside and outside the machines. This approach minimised interference with operator productivity, as it eliminated the need for evaluators in the field. Additionally, it enabled precise identification of operational activities, reducing the time required for data collection.

A subsequent comparison of load capacities was conducted between the Elephant and Elephant King forwarders in stands with an Average Volume per Tree (AVT) ranging from 0.19 to 0.23 m^3 wb. A preliminary study determined that, on average, operators required 20 full crane loads (each crane load covering an area of 0.42 m^2) to completely load the forwarder's cargo box under the conditions assessed. Nine trials were performed with the Elephant forwarder, three with the Elephant King in its standard configuration, and three in an extended configuration, where the Elephant King's cargo box gate was raised to its maximum height.

Economic Evaluation

The economic analysis focused on accurately quantifying all operational and production costs associated with the forwarder. All equations used in this analysis are based on the standardised guidelines established by the ASAE – American Society of Agricultural and Biological Engineers (2011) – and have been widely applied in consolidated studies such as Ferreira et al. (2025) and Lima et al. (2025). For currency conversion, the exchange rate of R$ 5.1186 per USD, as recorded on April 14, 2024, was applied.

To calculate the operational costs of forest extraction activities, all contributing elements to the execution of these operations were identified, including personnel, material, equipment maintenance and transportation costs, among others. These costs must be summed to determine the total cost of operations, as expressed in equation 2:

$$CT = CF + CV \quad \text{(equation 2)}$$

where *CT* is the total operational costs (USD/he); *CF* is the fixed costs (USD/he); *CV* is the variable costs (USD/he).

Production costs were calculated based on the volume, expressed in dollars per cubic meter harvested (USD/m^3) for each type of machine, according to equation 3:

$$CP = \frac{CT}{P} \quad \text{(equation 3)}$$

where *CP* is the production cost of the machines (USD/m); *CT* is the total operational cost of the machinery (USD/he); *P* is the productivity of the evaluated machines (m^3/he).

This cost was determined by the ratio between the operational cost and the effective productivity of the machines, considering the scenarios of Average Volume per Tree (AVT) described in this study. This allowed for the identification of the equipment most sensitive to changes in AVT. The fixed costs analysed included depreciation, interest, insurance, taxes (equations 4 and 5), storage (equation 6), and administrative fees (equation 7):

$$MAI = \frac{(Va - Vr)(N + 1)}{2N} \quad \text{(equation 4)}$$

$$IIT = \frac{MAI * i}{he} \quad \text{(equation 5)}$$

$$S = \frac{Va * SF}{he} \quad \text{(equation 6)}$$

$$AR = \frac{Va * AF}{he} \quad \text{(equation 7)}$$

where *Va* is the acquisition cost (Log Loader $129,211.42); *Vr* is the residual value of the machine (10% * *Va*); *IIT* is the interest, insurance, and taxes; *MAI* is the annual average investment; *i* is the interest rate (12%); *he* is the annual productive usage hours (4,045.86 he); *N* is the useful life (5 years); *S* is the storage facility; *SF* is the storage facility factor (0.75%); *AR* is the administrative fees and *AF* is the administrative factor (4%).

The variable operating costs included: fuel (equation 8), lubricants (8.0% of the fuel cost), hydraulic oil (16.0% of the fuel cost), tracks (equation 9), maintenance and repairs (equation 10), labour (equation 11), labour transportation (equation 12), and machinery transportation (equation 13):

$$F = FP * FC \qquad \text{(equation 8)}$$

$$TC = \frac{NT * Vpe}{HPE} \qquad \text{(equation 9)}$$

$$MR = \frac{\left[Va * FR1 * \left(\frac{h+he}{1000}\right)^{FR2}\right] - \left[Va * FR1 * \left(\frac{h}{1000}\right)^{FR2}\right]}{he} \qquad \text{(equation 10)}$$

$$MO = \frac{MOW * Tx * No * M}{he} \qquad \text{(equation 11)}$$

$$MTC = \frac{ADD * ck * dwy}{he * Ne} \qquad \text{(equation 12)}$$

$$TM = IMT * MTC \qquad \text{(equation 13)}$$

where *F* is the final fuel cost; *FP* is the fuel price (USD 1.32/L); *FC* is the fuel consumption (20.5 L/h); *TC* is the cost of tracks; *NT* is the number of tracks; *Vpe* is the price per track (USD 8,010); *HPE* is the service life of the track (12,500 hours); *MR* is the cost of maintenance and repairs; *FR*1 is the repair factor 1 (0.005); *FR*2 is the repair factor 2 (2); *h* refers to the accumulated hours of use up to the start of the evaluation (2,113.82 hours); *MO* is the labour cost; *MOW* is the operator's monthly wage (USD 910.22); *Tx* is the labour rate (3.0); *No* is the number of operators (3); *M* is the number of months (12); *MTC* is the labour transportation cost; *ADD* is the average daily distance travelled to transport workers to the sites (220 km/day); *ck* is the cost per kilometre (USD 1.62/km); *dwy* is the number of working days in a year (365); *Ne* is the number of workers per transport vehicle (18); *TM* is machinery transportation; *IMT* is the machinery transportation index (75%); *MTC* is the labour transportation cost.

Statistical analysis

The statistical procedures adopted in this study were based on the methodological approach used by Lima et al. (2025) in a similar assessment of forestry machinery. For regression analysis, statistical correlation, mean tests, descriptive statistical inferences, and result presentation, the software "GraphPad Prism 8", "Statistica 7.0", and "SPSS 11.0" were used. For statistical analysis of equations, the selection criteria prioritised productivity equations with the highest coefficient of determination (R^2), followed by models with fewer variables. To compare the mean cycle times of the forwarder, ANOVA (Analysis of Variance) and the Student–Newman–Keuls test for multiple comparisons were applied, with a significance level of 5%.

Linear correlation analyses were conducted on productivity data (m^3/hr) for the forwarder, verified by Pearson's correlation test at a 1% significance level. Subsequently, results were compiled along with regression models, and graphs were created for each scenario using "GraphPad Prism 8".

The fitted models were then compared according to Burnham and Anderson (1998) using the Akaike Information Criterion (AIC) to determine which model best describes the productivity of the forestry machinery. To assess dependency, the stepwise regression method was applied at a 5% significance level (Hastie et al. 2009), with variables not showing statistically significant influence excluded from the models.

Results

Performance evaluation of forest extraction machinery

The productivity curves for the forwarder, expressed in cubic meters per effective working hour (m^3/he), were modelled as a function of the Average Volume per Tree (AVT) across scenarios with varying extraction distances in both first-rotation and second-rotation (coppice) plantation areas (figure 3). These models revealed high coefficients of determination (R^2) and robust statistical correlations (r), indicating a strong predictive relationship between AVT and productivity under different extraction distances. Such insights emphasise the forwarder's efficiency variations in response to forest type and extraction conditions, providing a valuable basis for operational planning and resource allocation.

Interpreting the prediction curve for model "A" reveals that machine productivity increases with higher Average Volume per Tree (AVT) classes, attributed to the faster filling of the forwarder's load box. Analysis of models "B" and "C" indicates an average forwarder speed of 4.16 km/h in first-rotation plantation areas and 3.98 km/h in second-rotation (coppice) plantation areas.

While these models individually do not precisely predict productivity, an acceptable extraction distance of up to 250 m showed a productivity reduction of up to 38% in first-rotation plantation areas and 3.98 km/h in second-rotation (coppice) plantation areas when extraction distances reached 500 m. The descriptive statistics of the tested variables are presented in table III.

The mean and median productivity values (m^3/h) are closely aligned, suggesting a data distribution that is reasonably symmetrical around the mean. Furthermore, the high coefficient of determination (R^2) for the forwarder as a function of AVT (A) indicates a strong predictive relationship. The large sample size and the excellent predictive performance of the model for the studied regions are noteworthy.

Although the technical models "B" and "C" presented lower R^2 values, both still exhibited good predictive behaviour for forwarder productivity. Productivity decreased as the extraction distance increased, with both models demonstrating a clear trend in this relationship.

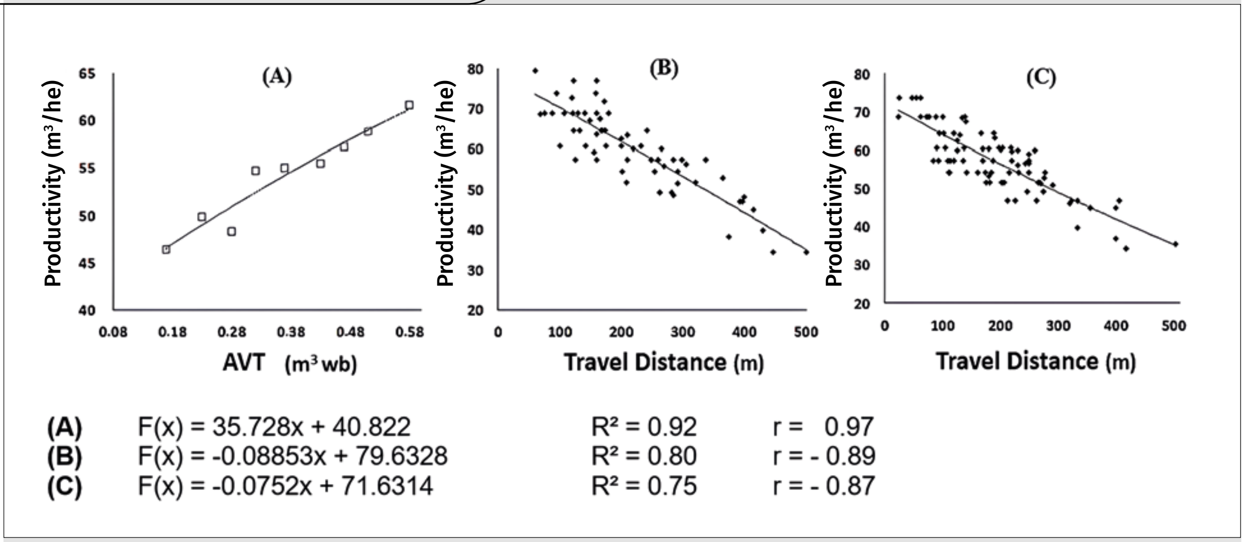

Figure 3.
Productivity function models for forestry operations: (A) Forest extraction with forestry forwarder in forests with varying productivity levels; (B) Forest extraction with first-rotation plantations; (C) Forest extraction with Forestry forwarder in second-rotation plantations.

The linear correlation coefficients (r) for the forwarder productivity models in relation to extraction distance (B and C) showed a strong inverse proportional correlation. This indicated that as the extraction distance increased, productivity consistently decreased. Despite the robust relationship between distance and productivity, the models displayed a moderate coefficient of determination (R^2), suggesting that extraction distance explains up to 80% of the variation observed in productivity. This points to the influence of additional factors, such as terrain slope, operator experience and training, and edaphoclimatic conditions – which encompass both soil properties (e.g., texture, compaction, moisture) and climatic variables (e.g., precipitation, temperature) – all of which must be thoroughly considered in both the analysis and interpretation of results. These factors should also be taken into account when developing strategies to optimise forwarder productivity. The coefficient of variation (CV) for the forwarder models indicated low variability relative to the mean, demonstrating relatively consistent performance across the different scenarios. These statistical approaches offer a comprehensive understanding of the variations in operational cycle times, costs, and productivity of machinery, enabling a more precise analysis of the factors influencing forest extraction efficiency. By examining these variations, decision-makers can identify key areas for improvement, optimise processes, and implement strategies that enhance overall productivity while reducing costs. This approach facilitates evidence-based decision-making, ensuring that operational adjustments are not only effective but also aligned with the long-term sustainability and efficiency goals of forest extraction operations.

Table III.
Analysis of descriptive statistics of productivity (m³/he) of forestry machinery operations in south-eastern Brazil.

Variable	Average	Median	σ	CV (%)	N
Forestry forwarder x AVT	54.16	52.66	8.12	15	2,250
Forestry forwarder x Distance in first-rotation plantation	53.07	51.21	6.12	11	86
Forestry forwarder x Distance in second-rotation plantation	49.05	48.68	6.33	13	64

AVT: average volume of tree without bark; σ: standard deviation;
N: number of sampled data points; . CV (%): coefficient of determination.

Assessment of production capacity and operational cycles of forest extraction machinery

The study of productive capacity based on the operational cycles of the forwarder is presented in figure 4 and table IV.

In the analysis of the forwarder's production capacity, it was found that with a spacing of 5.0 × 2.40 m, the distance between wood piles was relatively long, reaching an average of 9.9 m between piles. This long spacing hindered loading from both sides of the line. Conversely, in areas with a spacing of 4.0 × 3.0 m, the piles were positioned at an average distance of 6.0 to 6.5 m, enabling loading from both sides of the track.

An analysis of the forwarder's operational cycle stages (figures 4-A, 3-B, and 4-C) revealed significant differences between first-rotation tree plantations and second-rotation plantation areas. In both cases, the loading phase accounted for the longest duration within the cycle. However, in second-rotation areas, the unloading and loaded travel phases required significantly more time ($p < 0.05$). This variation suggests that the operational cycle is influenced by forest rotation, directly impacting the machine's performance and efficiency.

The increased time spent on unloading and travelling loaded areas in second-rotation (coppice) plantation

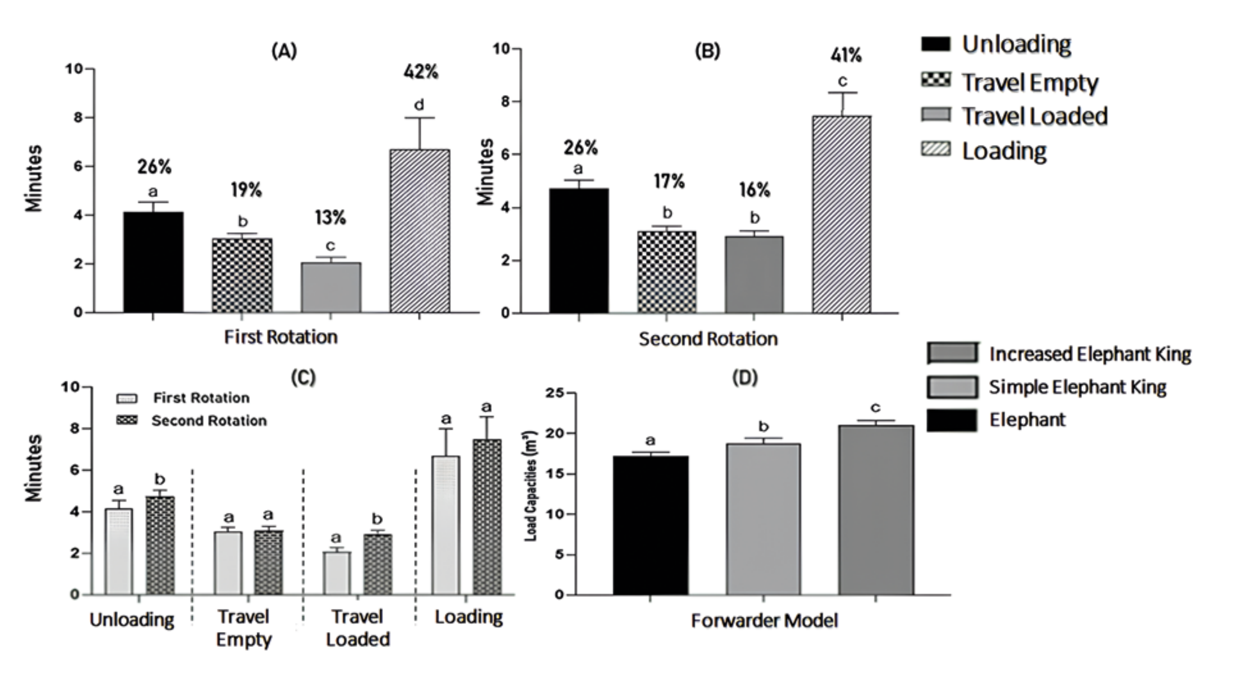

Figure 4.
Study of the production capacity and operational cycle of the forestry forwarder: (A) Time distribution and comparison of the forestry forwarder's operational cycle stages in first-rotation plantations; (B) Time distribution and comparison of the forestry forwarder's operational cycle stages in second-rotation plantations; (C) Comparative analysis of the forestry forwarder's operational cycle stages between first-rotation planted forests and second-rotation plantations; (D) Load capacity of the forestry forwarders Elephant, Elephant King simple, and Elephant King increased. Means followed by different letters within the same graph are statistically different according to the Student-Newman-Keuls test at a significance level of $p < 0.05$. The percentages in graphs A and B represent the time distribution in each stage of the operational cycle, based on time and motion study for first-rotation (A) and second-rotation (B) plantations.

areas can be attributed to the higher number of logs per unit volume, which demands additional time for stacking at the roadside. Furthermore, differences in tree morphology between rotations – such as smaller Average Volume per Tree (AVT), greater presence of branches, and more stem imperfections in second-rotation forests – may contribute to variations in cycle efficiency, highlighting the need for adaptive operational strategies. These findings align with predictive regression models and field observations, reinforcing the relationship between forest productivity and the time allocation of the forwarder across different operational stages.

The loading phase of the forwarder accounts for up to 42% of the machine's operational cycle. By loading from both sides of the line, productivity improves, leading to a reduction in production costs. This highlights the critical importance of the final stage of extraction with the forwarder, as efficient wood stacking during the unloading phase significantly enhances the subsequent loading process performed by the log loader. Efficient stacking and unloading ultimately optimise the entire forest harvesting cycle, increasing overall operational efficiency and reducing downtime.

In the second-rotation forest, the average extraction distance was 223 m, with the machine working on only one side of the line. Specifically, 51 m was the distance travelled to complete the forwarder's load capacity, and 172 m was travelled when fully loaded. As a result, the total operation time was 18.2 min, corresponding to an average productivity of 56.70 m^3/he. In the second rotation forest, the average speeds for the forwarder when empty and loaded were similar, at 3.93 km/h and 4.04 km/h, respectively.

In the first-rotation forest, the average extraction distance was 200 m, again with the machine working on only one side of the line. Here, 41 m was the distance travelled to complete the forwarder's load capacity, and 159 m was travelled when fully loaded. Consequently, the total operation time was 15.93 min, resulting in an average productivity of 64.78 m^3/he. In this forest, the average speeds for the forwarder when empty and loaded were similar as well,

Table IV.
Operational and performance metrics of the forwarder.

Operational characteristics	First Rotation	Second Rotation
Average extraction distance (m)	200	223
Distance travelled to full load (m)	41	51
Distance travelled when loaded (m)	159	172
Total operation time (min)	15.93	18.2
Average productivity (m^3/he)	64.78	56.70
Average speed when empty (km/h)	4.47	3.93
Average speed when loaded (km/h)	3.86	4.04

at 4.47 km/h and 3.86 km/h, respectively. The time and motion study showed higher productivity in the forest with a greater Average Volume per Tree (AVT) in the first-rotation forest compared to the second-rotation forest.

The load assessment of the forwarder models, Elephant and Elephant King, demonstrated very low standard deviation (figure 4-D). The Elephant forwarder's loads had an average volume of 17.18 m³, with a coefficient of variation (CV) of 1.68%, indicating high homogeneity and reliability. Both configurations of the Elephant King (single and extended) showed low standard deviation values, with CVs up to 3.17%, further confirming the homogeneity and dependability of the measured data.

In the most common operational configuration, the forwarder Elephant King demonstrated an average load box capacity of 18.79 m³. At its maximum capacity, the forwarder Elephant King achieved an average of 21.05 m³ per trip, representing a 22.52% increase compared to the Elephant and a 12.02% increase compared to the single-adjusted Elephant King. However, it is recommended to use the forwarder Elephant King with its extended load capacity only on flat terrain and in the absence of prolonged periods of precipitation. This approach allows for both economic and environmental benefits, including reduced soil compaction and lower production costs.

Production cost optimisation

The economic analysis of the forwarder revealed an annual total cost of USD 928,828.85, resulting in a cumulative lifetime cost of USD 4,644,144.27. Based on these findings, optimised production cost projections for the forwarder were estimated and presented in tables (tables V and VI), considering operational variables, forest characteristics, and specific aspects of the extraction operation.

Based on the productivity equations and the calculated operational costs, it was found that in more productive tree plantations (with an Average Volume per Tree, or AVT, of 0.55 m³) extraction costs were lower, amounting to 2.63 USD/m³ wb. In contrast, in less productive plantations (with an AVT of 0.15 m³), the extraction costs increased to 3.32 USD/m³. This represents a 26% increase in cost per cubic meter, which reinforces the inverse relationship between AVT and extraction costs in USD/m³.

Furthermore, extraction distance emerged as another critical factor directly influencing the operational costs. In plantations with shorter extraction distances (50 m), the cost was 2.11 USD/m³ wb for first-rotation forests and 2.34 USD/m³ wb for second-rotation plantations. However, when the extraction distance increased to 450 m, the costs rose to 4.00 USD/m³ wb and 4.21 USD/m³ wb for first and second rotation plantations, respectively. These findings indicate that extraction costs experienced a cumulative increase of 61% as the extraction distance grew, irrespective of the plantation rotation.

Discussion

Forest harvesting in Brazil is primarily conducted through two predominant systems: cut-to-length and full-tree (Amorim et al. 2021). This study specifically evaluated operations within the cut-to-length system, which is widely employed in eucalyptus harvesting for the pulp and paper industry. In this system, trees are processed at the felling site, and logs are transported by forwarders to roadside landings (Silva et al. 2022; Holzleitner and Kanzian, 2021). The way in which forwarder loading and transportation are executed has a direct impact on the performance of other harvesting machines, such as harvesters and feller

Table V.
Production costs (USD/m³) of forwarder extraction based on the average volume of trees without bark (AVT) in tree plantations.

AVT (m³ wb)	Production costs (USD/m³)	Cost increase (%)
0.15	3.44	-
0.20	3.32	-4%
0.25	3.20	-4%
0.30	3.09	-3%
0.35	2.98	-3%
0.40	2.89	-3%
0.45	2.80	-3%
0.50	2.71	-3%
0.55	2.63	-3%

AVT: average volume of tree without bark.

Table VI.
Forwarder extraction production costs based on extraction distance (ED) in first-rotation and second-rotation plantation areas.

ED (m)	First-rotation		Second-rotation	
	Production costs (USD/m³)	Cost increase (%)	Production costs (USD/m³)	Cost increase (%)
50	2.11	-	2.34	-
100	2.25	6%	2.48	6%
150	2.50	7%	2.64	6%
200	2.57	7%	2.81	7%
250	2.77	8%	3.01	7%
300	3.00	8%	3.24	8%
350	3.27	9%	3.51	8%
400	3.60	10%	3.83	9%
450	4.00	11%	4.21	10%

bunchers, as well as the stacking of logs for subsequent loading by log loaders (Lima et al. 2019; Lima et al. 2025). Therefore, understanding the productivity and operational dynamics of forwarders is crucial for optimising the overall harvesting flow, improving equipment utilisation, and reducing costs across the wood supply chain.

A comparative analysis between the results obtained in this study and evidence from the literature provides critical insights into the factors influencing forwarder productivity, distinctly differentiating between modifiable and non-modifiable variables.

Among the modifiable factors, average volume per tree (AVT) stands out, exhibiting a strong correlation with forwarder productivity. This finding aligns with recent studies indicating that increasing AVT can enhance operational efficiency by reducing cycle time and extraction costs per cubic meter (Lima et al. 2025; Ferreira et al. 2025). Furthermore, planting spacing configuration has been proved crucial for loading efficiency, corroborating research showing that larger distances between woodpiles may hinder forwarder operation (Papandrea et al. 2025). The choice of harvesting system also directly impacts productivity, with systems optimised for specific terrain conditions significantly reducing operational costs (Temba et al. 2023).

Conversely, non-modifiable site characteristics such as extraction distance and terrain slope continue to exert a substantial influence on forwarder productivity. Recent field data and regression modelling indicate that as extraction distance increases, fuel consumption per cubic meter (L/m³) and cycle times rise significantly – for every additional 100 m of forwarding distance, fuel use increases by approximately 0.05 L/m³ (Kärhä et al. 2023). Simultaneously, operating on steep or soft terrain elevates hourly fuel consumption and reduces average speeds (Bacescu et al. 2024). Additionally, Palander (2025) highlights that fuel consumption varies according to slope, with cut-to-length harvesting on sloped terrain resulting in up to 15% higher fuel use than on flat areas.

Given this body of evidence, several key aspects emerge as critical drivers of forwarder productivity and operational costs. The Average Volume per Tree (AVT) stands out as a pivotal factor for optimising harvesting operations, while extraction distance underscores inherent limitations imposed by fixed site characteristics. The robustness of the applied statistical models strengthens the understanding of productivity variations, providing a solid foundation for practical forest management decisions. Furthermore, the economic analysis derived from these results highlights promising avenues for future research aimed at enhancing both efficiency and sustainability in forest operations.

Effect of Average Volume per Tree (AVT) on forwarder productivity

The study identified Model A (figure 3) as the most effective in explaining forwarder productivity, demonstrating that as Average Volume per Tree (AVT) increases, machine productivity also improves. This finding aligns with previous research (Malinovski et al. 2006; Lima et al. 2024b), which highlights that larger tree volumes facilitate better log arrangement and enhanced cargo box utilisation, ultimately increasing efficiency in timber extraction.

The relationship between AVT and productivity is well documented in the literature. Proto et al. (2017) and Silva et al. (2023) emphasise that a higher AVT directly correlates with improved efficiency in timber extraction operations, reinforcing the importance of selecting and managing forest stands with larger tree volumes to optimise performance. Additionally, beyond AVT, factors such as terrain slope, precipitation levels, and operator expertise (Manner et al. 2016) play a crucial role in influencing productivity. These operational variables should be incorporated into predictive models to enhance decision-making in timber harvesting, providing a more comprehensive approach for future research.

Impact of extraction distance on productivity and costs

In contrast to AVT, Models B and C (figure 3) revealed a negative correlation between extraction distance and forwarder productivity, a result consistent with Eriksson and Lindroos (2014). Longer extraction distances lead to increased travel time per cycle, reducing the number of loads transported per hour.

Existing literature supports this observation. Gagliardi et al. (2020) and Masioli et al. (2024) report that loading and unloading stages account for most of the operational time in wood extraction, suggesting that transportation time alone is not the primary determinant of productivity. Manner et al. (2016) further observed that time consumption per load is more affected by load handling efficiency than by extraction distance.

From an economic standpoint, the study showed that extraction costs increased by 61% with distances up to 450 m, a trend also identified by Spinelli et al. (2020) and Proto et al. (2017). This finding underscores the importance of strategically locating log landings to minimise unnecessary machine travel and reduce operational costs.

Statistical analysis and practical implications

The descriptive statistical analysis (figure 3) revealed closely aligned mean and median productivity values, indicating a symmetrical data distribution. The low coefficients of variation (CV) suggest high data homogeneity, reinforcing the reliability of the observed trends. Longer extraction distances lead to increased travel time per cycle, reducing the number of loads transported per hour. The high coefficients of determination (R^2) and strong statistical correlations (r) further substantiate these findings, confirming the robustness of the models in reflecting operational realities. As demonstrated in this study, Gagliardi et al. (2020) emphasise that forestry companies can develop their own productivity models tailored to various edaphoclimatic and operational conditions in diverse scenarios.

This aligns with the findings of Rukomojnikov et al. (2024), who demonstrated a mathematical dependency between loading zone placement and forwarder efficiency. The study showed that optimising log collection work positions and landing areas could significantly improve productivity.

A key operational takeaway is that using both sides of the extraction line for loading can enhance efficiency, as demonstrated in studies by Schettino et al. (2022) and Lima et al. (2023). Implementing these techniques in forestry operations could lead to tangible reductions in total cycle time.

Economic considerations and future research directions

The economic analysis revealed an annual forwarder operational cost of USD 928,828.85 and a life-cycle cost of USD 4,644,144.27, with a 26% increase in cost per cubic meter as AVT decreases. This aligns with the cost behaviour patterns described by Purfürst and Erler (2011) and Liski et al. (2020), which highlights the inverse relationship between tree volume and operational costs. As AVT increases, more efficient log arrangement and cargo capacity utilisation contribute to reduced extraction costs, reinforcing the importance of managing forest stands to optimise productivity. In this context, variables related to AVT and machine operators are key factors influencing operational efficiency, accounting for over 80% of the variation in work productivity; this significant impact directly affects production costs (Purfürst and Erler, 2011; Liski et al. 2020).

In this context, according to Stoilov et al. (2023), the smallest fraction of the forwarder's costs is fixed, accounting for about 8% of the €25.33 per effective hour in their study. Additionally, studies by Rocha et al. (2022) and Munis et al. (2023b) indicate that costs related to labour, lubricants, and maintenance tend to rise in proportion to machine utilisation rates. While higher productivity can drive efficiency gains, it can also lead to increased operational expenditures due to more intensive machine usage (Stoilov et al. 2023; Munis et al. 2023a).

Understanding machine productivity is crucial for managing the total costs of the cut-to-length system, as extraction operations represent a significant portion of timber production expenses (De Assis Costa Ferreira et al. 2023). The results indicate substantial variations in production costs related to Average Volume per Tree (AVT) and extraction distance, with a cost reduction of approximately 23% as AVT increases from 0.15 to 0.55 m^3 per tree, and cost increases of up to 90% as extraction distances range from 50 to 450 m. These findings align with recent international studies highlighting the decisive influence of machinery configurations and operational parameters on productivity and economic efficiency. For example, Lundbäck et al. (2024) demonstrate that forwarders equipped with rubber tracks maintain higher operational speeds over long extraction distances, mitigating cost escalations related to travel. Their study also identifies a cost equilibrium between tracked and wheeled forwarders at distances between 400 and 700 m, emphasising the importance of selecting machinery suited to specific site conditions.

Forest extraction operations remain challenging and complex due to the interplay of several factors that directly affect productivity, including forest density, operator skills, work techniques, and the characteristics of forestry machinery (Kamarulzaman et al. 2022; Aworka et al. 2022). Understanding these interrelated variables is essential for effective management and sustainable planning of the cut-to-length system, enabling optimised resource allocation and improved operational efficiency.

Factors such as operator skill level, forest density, species composition, climatic conditions, and log stacking configurations further influence forwarder efficiency and should be incorporated into predictive models. By integrating these variables, forestry companies can enhance decision-making processes and optimise forwarder performance under different operational conditions (Labelle et al. 2018; Picchio et al. 2020; Lima et al. 2023).

Finally, it is essential to recognise the need for similar studies in different operational and edaphoclimatic conditions, as this promotes productive adjustments and enables the specific use of forestry extraction machinery focused on enhancing operational efficiency (Melchiori et al. 2022; Ghotb et al. 2023). Factors that could enhance future studies include operator experience, tree size, forest density, species composition, forest management practices, forest rotation, topography, machine capacity, soil type, climatic factors, extraction distance, log stacking at the forest edge, and operator expertise (Labelle et al. 2018; Picchio et al. 2020; Luo et al. 2021; Lima et al. 2023).

Conclusion

Based on the study's analyses, several actionable strategies can be implemented by forest managers. Operational changes may include adjusting harvesting layouts to reduce average extraction distances, deploying forestry forwarders with greater load capacity to improve productivity per cycle, and refining equipment allocation based on terrain and precipitation risks. Silvicultural planning can also be informed by the demonstrated relationship between AVT and cost-efficiency, encouraging strategies that promote higher stem volume per tree where feasible. When contextualised within the broader forest value chain, the quantified gains in productivity and cost – such as the 26% reduction in unit cost associated with increased AVT – should be interpreted relative to total wood production costs, including transportation and processing. For instance, in high-volume operations with overall wood costs at the factory yard ranging between 40 and 60 USD/m^3, a reduction of 1.00 to 1.50 USD/m^3 in extraction cost represents a significant improvement in profitability and operational efficiency. Thus, this study provides not only technical evidence but also economic benchmarks to support better financial planning and resource use in forest operations.

This study aimed to assess the factors influencing forest forwarder productivity and extraction costs, particularly how extraction distance, Average Volume per Tree (AVT), and operational conditions affect mechanised extraction efficiency. The predictive models developed explained up to 92% of the variability in forest forwarder productivity (m^3/h), reinforcing their utility for operational planning.

The results confirmed an inverse linear relationship between productivity and extraction distance, and a direct proportionality with AVT. While these findings may seem intuitive, their quantification provides objective thresholds to support decision-making. For example, as extraction distance increased from 50 to 450 m, total extraction costs rose by 61%, while productivity declined proportionally. Conversely, an increase in AVT from 0.15 to 0.55 m^3/tree led to a 26% reduction in production costs per cubic meter. These quantifications help forest managers define economically viable extraction limits and prioritise management strategies that maximise value per trip. From an operational standpoint, the study revealed that the forestry forwarder loading process accounts for up to 42% of the machine's operational cycle, indicating a critical area for optimisation. The use of forestry forwarders with higher load capacities is recommended, as they maximise extraction efficiency, averaging 21.05 m^3 per trip. However, environmental factors, particularly precipitation and slope, must be carefully considered to ensure safe and sustainable operations.

From a practical standpoint, reducing extraction distance may involve directing tree felling through mechanised harvesters or feller-bunchers, reconfiguring extraction routes, optimising the layout of primary and secondary forest roads, or planning harvest sequences that minimise machine travel. Although AVT is partly constrained by species growth and silvicultural regimes, forest managers can influence this variable through appropriate site selection, deployment of high-yield clones, rotation planning, and silvicultural treatments aimed at improving stem form and increasing volume increment. Additionally, prioritising the harvesting and development of company-owned forest stands – instead of sourcing timber from external or distant areas – can significantly reduce extraction distances and associated operational costs, while fostering more productive forests with higher AVT values.

The economic analysis shows that extraction costs increase with extraction distance and decrease with higher Average Volume per Tree (AVT) values. Specifically, as AVT increased from 0.15 to 0.55 m^3 per tree, production costs decreased by approximately 26% per cubic meter. Conversely, when extraction distances increased from 50 to 450 m, total extraction costs cumulatively rose by 61%. These variations are associated with reductions in productivity and increases in operational time, highlighting the critical impact of these variables. For example, at an extraction distance of 50 m, production costs were 2.34 USD/m^3, rising to 4.21 USD/m^3 at 450 m, with a proportional decrease in productivity. These data provide concrete parameters for defining optimal operational ranges within the region, contributing to improved economic planning and enhanced efficiency of forestry operations.

The study's implications extend to both academic research and operational forestry, offering a data-driven framework for optimising timber extraction, minimising operational costs, and enhancing machine utilisation efficiency. Future research should aim to validate these results across diverse edaphoclimatic conditions – defined as the combined influence of soil properties such as compaction, fertility, and moisture, and climatic factors such as temperature, rainfall, and humidity – and refine predictive productivity and cost models.

Additionally, further investigations should focus on operational strategies to improve the loading phase of the extraction cycle. Moreover, subsequent studies must incorporate considerations of occupational safety and environmental sustainability, ensuring that mechanised forest operations are aligned with best practices in both economic performance and ecological responsibility.

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Data access

The data is available by using the following Internet link and citing the origin with the citation:

Lima C. F., De Assis Costa Ferreira F., Lima R. C. A., Minette L. J., Silva A. A., De Freitas L. C., Schettino S., Said Schettini B. L., Da Silva Leite E., Guimarães Veloso A. C., Lima F. A., 2024. Supplementary Material. figshare. Dataset. https://doi.org/10.6084/m9.figshare.27934059

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