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Optimal Forest Road Density as Decision-Making Factor in Wood Extraction

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Abstract: Forest road construction projects mainly depend on factors related to terrain physiography, watershed, and wood harvesting. In the whole tree system, wood extraction is the activity most impacted by the density of forest roads, influencing the extraction distance. One of the alternatives is the optimal forest road density approach, which allows for the minimization of wood extraction costs and the optimization of the productive area. Given the above, the objective of this study was to analyze whether the optimal forest road density in areas of forests planted with eucalyptus allows for maximum productivity and the lowest cost of the road-wood extraction binomial in a whole tree system. The technical and economic analysis of wood extraction was based on the study of time, operational efficiency, productivity, and the cost of wood extraction with a grapple skidder. For the optimal forest road density, the cost of the wood extraction activity was considered, as well as the cost of construction, reconstruction, and maintenance of roads. In addition, the cost of a loss of productive area and the cost of excess forest roads were weighted. The optimal forest road density was 30.49 m ha^{-1} for an average extraction distance of 81.99 m, with the cost of loss of productive area of 0.49 USD m^3 and the excess road of 80.19 m, which represented a cost of 978.31 USD ha^{-1}. It is concluded that the optimal forest road density allows for the identification of excess forest roads, allowing for a reduction in the total cost for the implementation of roads. Therefore, it can be considered an essential variable in the planning of the forest road network, providing improvements in productivity and the costs of wood extraction with a grapple skidder.

Keywords: wood harvesting; forest roads; grapple skidder; cost; productivity

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1. Introduction

The operational planning of wood-harvesting activities is an indispensable requirement, mainly due to the demand for high-productivity planted forests, to meet the needs of forestry companies and their products, such as sawn wood, paper, and cellulose.

Among the mechanized wood-harvesting systems in Brazil, the whole tree stands out. In this system, trees are felled using self-propelled forest machines called feller bunchers. Then, the wood is extracted from inside the stands to the edges of forest roads with the self-propelled forestry machine grapple skidder and, finally, the wood is processed by the grapple saw [1–4].

The grapple skidder has a tire-rolling system and the possibility of 4 × 4, 6 × 6, or 8 × 8 traction. This machine uses a suspended grapple to extract the wood by lifting the ends of the wood off the ground [5–8].

Grapple skidder productivity is affected by the operator's experience time, terrain slope, planting productivity, the forest species used, and mainly by the wood extraction distance. Therefore, as the extraction distance increases for the same volume of wood, its productivity decreases [9–11].

The extraction distance is one of the determining factors in the whole tree system, and a shorter extraction distance will provide a lower cost in the activity. However, this

distance influences the density of roads, demanding the use of models to determine its variables for good planning and the optimization of wood-harvesting operations [12–14].

The study of time is presented as a premise for this optimization, as it allows for the identification and quantification of the time spent by the grapple skidder in different extraction distance classes, allowing for an increase in the efficiency and productivity of this machine, in addition to reducing the extraction costs [15,16].

This study acts as a continuous procedure to improve productivity, establishing time patterns and classifying the predetermined movements by the grapple skidder, which are necessary for the execution of the activity. In addition, it shows the efficiency of the application of available resources in achieving work performance objectives [17].

At the same time, it is important to associate these distance classes with the costs of construction, maintenance, and the reconstruction of forest roads, and, consequently, with the optimal forest road density (ORD), in order to provide efficiency for harvesting and wood transport operations [18–32]. Forest roads can also work as firebreaks for fire prevention and control, in addition to helping create better access for firefighters to the place in question [33,34].

The ORD consists of a specific methodology for optimizing the number of forest roads, which results in a lower combined cost of road construction, reconstruction, and maintenance, in addition to reducing the cost of wood extraction [35]. The proper sizing of the ORD can indicate the optimization of the implantation of planted forests for commercial purposes, minimizing the number of forest roads and avoiding unnecessary losses of productive areas [24,36–39].

Applied in macro-planning forest decision-making, the ORD favors the allocation of the forest road network based on the physiography of the terrain, the watershed, and wood extraction, aiming at sustainability for the maximization of forest resources. This variable can be obtained through mathematical modeling or by geographic information systems, the latter of which uses satellite images [36,40].

The operation of wood extraction in planted forests without the ORD approach can technically and economically make wood harvesting unfeasible, require monetary expenditures for the unnecessary implementation of forest roads, and also compromise sustainable management.

In this context, the objective of this paper was to analyze whether the optimal forest road density in areas of forests planted with eucalyptus allows for better decision-making in the road-wood extraction binomial in a whole tree system.

2. Materials and Methods

2.1. Study Area

The study was carried out in a planted forest of *Eucalyptus urophylla* × *Eucalyptus grandis* in the first rotation, with 3 m × 2 m spacing, located under the geographic coordinates 23°06′ S and 48°36′ W, in the state of São Paulo, Brazil. The soil of the study area was classified as Red Yellow Latosol Dystrophic psammitic A moderate Alic medium texture [41].

The forest inventory of the experimental area was carried out by drawing lots at random, consisting of 400 m^2, and the Schumacher–Hall model was used to adjust the volumetric ratio [42]. The area was georeferenced to obtain points around the forest roads and to measure the widths and distances between the roads. The areas of the generated polygons were used to estimate the density of forest roads [43].

The company that owns this forest had a planted area of 32,584 ha of eucalyptus, in which the empirical data of the technical and economic coefficients were shared by the company that owns the forest plantation (Table 1). In addition, the areas have a slope from 0.0% (flat) to 45.0% (strong wavy), with a predominance of smooth wavy relief (3.0% to 8.0%) according to Jourgholami et al. [44], and 3606.63 km of forest roads.

Table 1. Technical and economic coefficients of planted eucalyptus forests in the state of São Paulo, Brazil.

Item	Unit	Value
The average width of forest roads	m	4.75
Average extraction distance	m	81.99
Mean age of clearcut	months	84.00
Average annual increment	m^3 ha^{-1} year	49.80
Diameter at chest height	cm	15.99
The average height of trees	m	25.25
Individual average volume	m^3	0.25
Average volume per hectare	m^3 ha^{-1}	331.41
Standing wood price	USD m^{-3}	3.24
Land price	USD ha^{-1}	4712.00

The purpose of these forests was the manufacture of laminated wood and sheets of plywood, pressed and agglomerated. The harvesting system used in these forests was the whole tree, through which self-propelled feller buncher machines were used to cut trees, a grapple saw was adopted for wood processing, and a grapple skidder was used for wood extraction.

2.2. Technical and Economic Analysis of Wood Extraction

The wood extraction was performed using a self-propelled forestry machine grapple skidder (Figure 1) from John Deere, model 848 H, with 149 kW of net engine power at rated speed, a tire system, and an operating mass of approximately 17,800 kg. The grapple had 1.5 m^2 of load accumulation capacity; in addition, there was a blade on the front that allowed for cleaning of the extraction aisles and contributed to the stacking of the wood logs.



Figure 1. Grapple skidder self-propelled forestry machine, John Deere, model 848 H.

The estimation, forecasting, and operational planning of the grapple skidder were based on the study of time [45]. The operational cycle was composed of the machine elements' displacement with no load; their displacement with a load; the loading of wood logs; and the unloading of wood logs. The calculation of the minimum number of operational cycles (Equation (1)) described by Stevenson [46], was estimated from a pilot study lasting 30 min, with a degree of precision of 95.0% and a sampling error of 5.0%.

$$n = \left(\frac{z\,s}{\varepsilon}\right)^2 \quad (1)$$

where n is the number of samples, z is the value of the standard normal distribution with the desired confidence level, s is the standard deviation, and ε is the standard error.

The operational efficiency of the grapple skidder (Equation (2)) allowed us to express the percentage of time effectively worked in relation to the total time programmed [47].

$$O_E = \frac{E_T}{T_p} \times 100 \quad (2)$$

where O_E is the operational efficiency (%), E_T is the effective working time (h), and T_p is the time programmed for working (h).

The time spent in the wood extraction activity by the grapple skidder (Equation (3)) is described by Carmo et al. [48]:

$$T_e = V_d + V_c + C_f + D_f \quad (3)$$

where O_E is the operational efficiency (%), E_T is the effective working time (h), and T_p is the time programmed for working (h). T_e is the time spent on the extraction (h), V_d is the unloaded travel time (h), V_c is the loaded travel time (h), C_f is the loading time of the tree (h), and D_f is the unloading time of the tree (h).

The average extraction distance (Equation (4)), the determinant for the choice of the wood-harvesting system and extraction costs, was expressed according to Heinimann [49]:

$$AED = \frac{2500 \times V \times T}{RD} \quad (4)$$

where AED is the average extraction distance (m), T is the correction factor for extraction for cases in which it is not performed in a straight line perpendicular to the road and does not end at the point closest to the origin (adopting 1 as a reference value), V is the correction factor for road networks, adopted when roads are tortuous and not parallel, with different spacing between them (adopting 1 as a reference value), and RD is the road density (m ha^{-1}).

Thus:

$$RD = \frac{LFR}{EPA} \quad (5)$$

where LFR is the length of the forest road (m), and EPA is the effective planting area (ha).

The displacement speeds of the grapple skidder with no load (Equation (6)) and with a load (Equation (7)) were also estimated according to Zagonel et al. [50]:

$$SNL = \frac{AED}{TNL} \quad (6)$$

where SNL is the average travel speed with no load (m min), TNL is the travel time with no load (min), and AED is the average extraction distance (m).

$$SWL = \frac{AED}{TWL} \quad (7)$$

where SWL is the average travel speed with a load (m min), TWL is the travel time with a load (min), and AED is the average extraction distance (m).

Weighing the times spent on the wood extraction activity and associating them with the volume of wood results in the estimation of the productivity per hour of the grapple skidder (Equation (8)) in line with Schettino et al. [51]:

$$P = \frac{V_w}{h} \quad (8)$$

where P is the productivity of the grapple skidder (m^3 h^{-1}), V_w is the volume of harvested wood (m^3), and h is the number of effective hours of the operation (h).

The estimation of the grapple skidder costs per scheduled hour (Table 2) was based on the expected economic life of the self-propelled forestry machine and on the respective operational efficiency, as proposed by Ackerman et al. [52].

Table 2. Grapple skidder costs per scheduled hour for eucalyptus wood extraction in São Paulo state, Brazil.

Factor	Unit	Value
Fuel consumption	L h^{-1}	25.92
Diesel price	USD L^{-1}	0.69
Tires	USD h^{-1}	13,000.00
Number of working days per year	days	362.00
Using the grapple skidder	%	60.20
Initial investment	USD	296,330.68
Residual value	USD	59,266.14
Operator salary	USD h^{-1}	6.43
Social charges	%	134.00
Property fee	USD h^{-1}	2963.31
Machine transport	USD h^{-1}	17,779.84
Insurance	USD h^{-1}	5926.61
Shelter	USD h^{-1}	14,816.53
Overhead	%	5.00

The cost of wood extraction (Equation (9)) was calculated as a ratio between the hourly programmed machine cost and productivity [53]:

$$C = \frac{MCH}{P} \tag{9}$$

where C is the cost of wood extraction (USD m^{-3}), MCH is the machine costs per hour scheduled (USD h^{-1}), and P is the productivity of the grapple skidder (m^3 h^{-1}).

2.3. Optimal Forest Road Density

The optimal forest road density (Equation (10)), considered a premise of management planning and, above all, an important indicator of suitability, was determined by the Food and Agriculture Organization [54]:

$$ORD = 50\sqrt{\frac{C \times T \times V \times q}{R}} \tag{10}$$

where ORD is the optimal forest road density (m ha^{-1}), C is the cost of wood extraction (USD m^3 km^{-1}), T is the correction factor for extraction for cases in which it is not performed in a straight line perpendicular to the road and does not end at the point closest to the origin (adopting 1 as a reference value), V is the correction factor for road networks, adopted when roads are tortuous and not parallel, with different spacing between them (adopting 1 as a reference value), q is the volume of wood harvested (m^3 ha^{-1}), and R is the cost of roads (USD km^{-1}).

Consideration should also be given to the approach related to the use of forest roads as firebreaks in preventing forest fires [55]. Thus, the study area was divided into forest stands, which had an average size of 50 ha, as recommended by Soares [56], for the relief conditions in Brazil.

The construction cost of roads (Equation (11)) represents the mobilization of production factors for the implementation of the forest road network:

$$Cc = \frac{COc + OCC}{AAI \times CA} \times RD \tag{11}$$

where Cc is the construction cost per linear meter of the road (USD m^{-1}), COc is the construction operation cost per linear meter of the road (USD m^{-1}), OCC is the annual opportunity cost of capital (USD m^{-1}), AAI is the average annual increment (m^3 ha^{-1}), CA is the court age (year), and RD is the road density (USD ha^{-1}).

Considering that the forest road network was consolidated, we estimated the costs inherent to road reconstruction (Equation (12)) according to Souza et al. [57]:

$$RC = \frac{(DCR + OCL) \times RD \times AFR}{VOL} \quad (12)$$

where RC is the reconstruction cost (USD m^{-1}), DCR is the annual depreciation cost of forest roads (USD km^{-1}), OCL is the annual opportunity cost of the alternative land use (USD km^{-1}), RD is the road density (m ha^{-1}), AFR is the total area with planted forests and roads (ha), and VOL is the total volume of wood (m^{-3}).

Due to the flow of vehicular combinations of cargo used to transport wood, trucks used to implement and maintain planted forests, and buses and vehicles used to transport forest workers, we calculated the cost of road maintenance (Equation (13)):

$$CRM = \frac{\sum(ARP \times RCH)}{1000} \quad (13)$$

where CRM is the cost of road maintenance (USD m^{-1}), ARP is the average resource productivity (h km^{-1}), and RCH is the resource cost per scheduled hour (USD h^{-1}).

The economic depreciation of the roads (Equation (14)) was estimated on an annual basis through straight-line depreciation [58]:

$$EDR = \frac{Cc}{LCR} \quad (14)$$

where EDR is the economic depreciation of roads (USD m^{-1}), Cc is the construction cost per linear meter of the road (USD m^{-1}), and LCR is the life of forest roads (years).

The annual opportunity cost of the alternative land use (Equation (15)) was estimated according to the methodology proposed by the United States Department of Agriculture [59]:

$$OCL = \frac{R}{2} \times i \quad (15)$$

where OCL is the annual opportunity cost of the alternative land use (USD m^{-1}), R is the cost of roads (USD km^{-1}), and i is the opportunity cost rate (%).

The opportunity cost rate (Equation (16)), denoted by i, was estimated using the Weighted Average Cost of Capital, because the company that owns the planted forest has a third-party equity interest, according to Vartiainen et al. [60]:

$$WACC = \frac{[D \times k_D(1 - CT) + E \times k_e]}{D + E} \quad (16)$$

where OCL is the annual opportunity cost of the alternative land use (USD m^{-1}), R is the cost of roads (USD km^{-1}), and i is the opportunity cost rate (%).

We added the 2.40% spread to the cost of third-party capital for countries with a Ba2 speculative credit rating [61]. The risk-free rate of return was 5.2%, obtained through the geometric average of the 10-year rate on Treasury bonds in the period between 1 February 1962 and 3 November 2021, according to data provided by the United States Department of the Treasury [62]. That said, the cost of third-party capital was 7.6%.

The cost of equity (Equation (17)) was obtained through the capital asset pricing model (CAPM) used to calculate the return on equity [63]:

$$k_e = R_{rf} + \beta_{mkt} \times \left(R_{mkt} - R_{rf}\right) + \alpha \quad (17)$$

where R_{rf} is the risk-free asset return (%), β_{mkt} is the market loading factor, exposure to market risk (%), and R_{mkt} is the market return; α is the country's risk premium (%).

The empirical measurement of the systematic risk coefficient (Equation (18)) was calculated according to Latunde et al. [64]:

$$\beta_{mkt} = \frac{Cov\left(K_j, K_m\right)}{\sigma_m^2} \quad (18)$$

where β_{mkt} is the leveraged beta index of the asset under analysis, $Cov\left(K_j,\ K_m\right)$ is the covariance between the return on the asset and the expected return for the market portfolio, K_j is the return of the asset under analysis, K_m is the expected return for the market portfolio, and σ_m^2 is the variance in the market portfolio return.

The leveraged beta ratio was estimated using the average of the unleveraged beta ratio of the companies Companhia Melhoramentos de São Paulo, Dexco S.A., Eucatex S.A. Indústria e Comércio, Klabin S.A. and Suzano Papel e Celulose S.A. These, belonging to the wood and paper sector, are listed on B3 S.A.-Brasil, Bolsa, Balcão [65], resulting in an unleveraged beta index of 0.27 for the wood and paper sector. When considering the participation of third-party capital of 43.2%, according to the balance sheet of the company that owns the planted forests, the average re-leveraged beta index of 0.35 was determined.

The market risk premium was 2.9%, calculated as the difference between the expected rate of return for the forest market portfolio, which was 8.1% according to data from the S&P Global Timber and Forestry Index [66], and the risk-free Asset return. The country's risk premium, obtained through the geometric average of the historical series of risks in Brazil between 29 April 1994 and 3 November 2021 and the Emerging Markets Bond Index Plus [67], was 3.9%.

The rate representing the cost of equity capital was 10.1%. Therefore, considering the proportion of equity of 56.8%, an opportunity cost rate of 7.9% was estimated.

The global cost of forest roads (Equation (19)) was estimated, which represents the cost of loss of the productive area, together with the costs of construction, reconstruction, and maintenance of forest roads [18]:

$$GCR = Cc + C + CPA \quad (19)$$

where GCR is the global cost of forest roads (USD m^{-3}), Cc is the construction cost per linear meter of the road (USD m^{-1}), C is the cost of wood extraction (USD m^{-3}), and CPA is the cost of loss of the productive area (USD m^{-3}).

The cost of excess forest roads (Equation (20)), a quantifiable measure that makes it possible to review the macro-planning of forestry companies, was estimated according to Campos et al. [68]:

$$CER = (Cc + RC + CRM) \times EFR \quad (20)$$

where CER is the cost of excess forest roads (USD ha^{-1}), Cc is the construction cost per linear meter of the road (USD m^{-1}), RC is the reconstruction cost (USD m^{-1}), CRM is the cost of road maintenance (USD m^{-1}), and EFR is the excess of forest roads (m ha^{-1}).

Thus:

$$EFR = RD - ORD \quad (21)$$

where EFR is the excess of forest roads (m ha^{-1}), RD is the road density (m ha^{-1}), and ORD is the optimum road density (m ha^{-1}).

3. Results

3.1. Technical and Economic Analysis of Wood Extraction

The sample sufficiency of the study included 1573 operational cycles, higher than the minimum number of cycles necessary for statistical legitimacy, which was 1017 cycles; therefore, the sampling error was reduced to 4.0%. With the completion of these operational cycles, it was possible to extract 6078 m^3 of wood.

The average operating cycle time was 4 min and 37 s. The machine element that required the most time was the displacement with a load with 47.5% of the operating cycle time, followed by the displacement with no load with 32.4%. The loading and unloading of wood logs represented 16.6% of the total operating cycle time, and nonproductive time, delays, and breaks accounted for 3.5%. Considering the volume of wood extracted and the total effective time of the activity, a productivity of 104.24 m^3 h^{-1} was obtained.

The grapple skidder cost per scheduled hour was 83.95 USD h^{-1}. Operator salary and fuel consumption costs accounted for 57.6% of the cost per scheduled hour, followed by maintenance and repair costs, which totaled 21.3%. The sum of the other costs related to the grapple skidder per hour scheduled for eucalyptus wood extraction represented 21.1%.

Reducing the average extraction distance decreased wood extraction costs and increased grapple skidder productivity (Figure 2). The longer extraction distances resulted in lower productivity values and higher wood extraction costs.

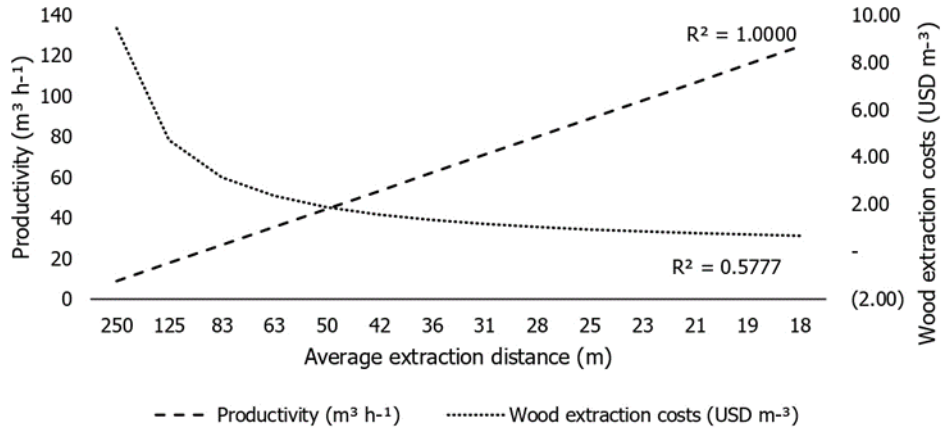

Figure 2. Relationship between productivity and cost of wood extraction with average extraction distance in eucalyptus plantations in the state of São Paulo, Brazil.

3.2. Optimal Forest Road Density

The optimal forest road density takes into account the current density of forest roads and the average extraction distance, together with the presence of firebreaks and the costs incurred. The road density was 110.68 m ha^{-1}, and the optimum road density was 30.49 m ha^{-1}. We calculated the excess of forest roads in 80.19 m ha^{-1}, resulting in the cost of excess forest roads as USD 978.31. With the quantification of the ORD, which was 30.49 m ha^{-1}, the study area presented an excess of roads of 263.0% when compared to the current density of roads.

The total cost of forest roads obtained after applying the ORD was 5.79 USD m^{-1}. The costs demanded for the reconstruction are the ones that most impacted the total costs, that is, they represented 70.6%. The economic depreciation costs of forest roads and maintenance accounted for 21.1%. The costs with the discount rate of the project due to the investment of capital were less representative, that is, 8.3%.

Regarding the implementation of roads, construction costs showed a directly proportional relationship with road density (Figure 3). The higher the road density, the higher the production costs of the wood extraction activity with the grapple skidder. However, as the cost of wood extraction decreases, road density increases, indicating an inversely proportional relationship.

The cost of loss of productive area presented a constant value of USD 0.49 m^{-1}, resulting from the average annual increase and the price of eucalyptus wood. The global cost of the forest roads presents a parabola-like behavior, with its inflection point indicating the ORD.

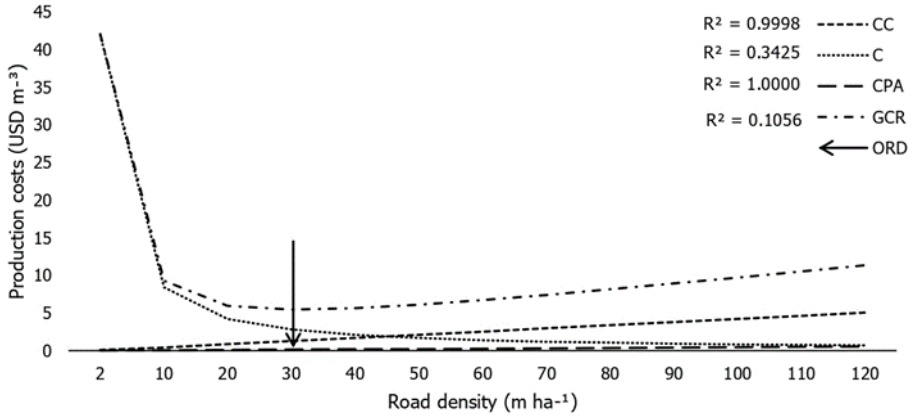

Figure 3. Relationship between road density and construction costs (CC), cost of wood extraction (C), the cost of loss of productive area (CPA), and the global cost of forest roads (GCR) for the whole tree-harvesting system.

4. Discussion

The sample sufficiency confirmed that the number of operational cycles observed was sufficient to determine the reliability of the study, reducing 1.0% of the minimum sample error initially admitted. Vasileiou et al. [69] and Li et al. [70] emphasize the importance of this approach to justify the size of a sample. Therefore, from the displacement with a load, which presented a higher standard deviation when compared to the other elements of the operational cycle, it was possible to estimate the minimum number of cycles and ensure the acceptability of the observed data.

When analyzing the time spent with the machine elements of the grapple skidder, it was found that the displacement time of the machine, with and with no load, was influenced by the size of the stands, which varied between 10.71 and 54.41 ha. Consequently, this variation interfered with the extraction distance and displacement times. In addition, extraction trail conditions, terrain slope, remaining stumps, harvesting residues, and wood extraction volume may have impacted operating cycle time [71–73].

Regarding the machine elements, the loading and unloading of wood logs, which represented 17.7% of the grapple skidder's operational cycle time, indicated that the size of the stands did not influence these parameters. Lopes et al. [47], Diniz et al. [74], Naderializadeh and Crowe [75], and Ross et al. [76] add that most of the operational cycle of this machine occurs actively, that is, is spent on activities associated with the greatest driving force of self-propelled forest machines. The optimization of the dimensioning of the stands in the forest areas is intended to adapt them to the management units, to facilitate silvicultural activities, fire prevention, and combat, and to minimize the operational cycle times of wood-harvesting activities. In this way, dividing the forest area into stands increase the productivity of self-propelled forest machines and minimizes wood extraction costs.

It was found that, with the decrease in the average extraction distance, the productivity of the grapple skidder increased. Associated with the operational predominance of machine elements of displacement with no load and displacement with a load, they resulted in a lower cost of wood extraction. It is noteworthy that the productivity of the grapple skidder is mainly influenced by the slope of the area, the individual average volume of the forest, the useful area of the grapple, and soil support capacity.

According to Kleinschroth and Healey [21] and Kweon et al. [77], the consideration of these elements is of paramount importance for planning the construction of forest roads. Therefore, if unweighted, this results in unnecessary travel, premature wear of self-propelled forest machines, and increased extraction costs. As a result, wood extraction is considered one of the critical points of wood harvesting due to its significant representation in the composition of the total cost of the production process [78–80].

Among the total costs of forest roads, the monetary expenditure demanded the reconstruction of forest roads be the most representative. However, according to Keller [81] and

Ghaffariyan [82], these expenditures can be acceptable when comparing forest roads that are low-volume roads, that is, with average traffic of up to 1000 vehicles per day, when compared to the reconstruction costs of high-volume roads.

The ORD obtained indicated the possibility of reducing the total cost of implementing roads by up to 47.0% and was therefore fundamental for decision-making in the rationalization of the road-wood extraction binomial. According to Naghdi and Limaei [83] and Havimo et al. [84], the correct implementation of the ORD in wood extraction areas helps in decision-making regarding the planning of the use of roads as routes for vehicle traffic. In addition, the ORD can be applied in the optimization of areas destined for the processing of extracted wood.

The quantification of the ORD made it possible to identify an excess of roads of 263.0%, resulting from a bad dimensioning of the forest road network. This excess interferes with the wood extraction directions, causing unnecessary displacements of the grapple skidder and the possible formation of woodpiles with less than the ideal amount of wood [85,86].

The costs related to excess roads, according to Campos et al. [68], can reach 200.0% of the implementation cost. Shadbahr et al. [87] indicate that the costs related to road construction are directly related to the current density of roads. Thus, the excess of roads is a determining variable for this financial expenditure, signifying the need to replan the roads to optimize resources.

The density of roads has an inverse relationship with the cost of wood extraction, that is, as the density of roads increased, there was a decrease in these costs. In this scenario, ORD acted to find the optimal point of road density relating to construction and wood extraction costs [88,89].

Considering the ORD in the planning of timber-harvesting operations has reduced extraction costs and increased the efficiency of forest road use [30]. In addition to contributing to an increase in forestry productivity, the ORD benefits the management of forestry projects, ensuring access conditions to the surroundings of the stands and forest machines for possible maintenance and supply [90,91].

5. Conclusions

The optimal forest road density makes it possible to obtain the maximum productivity and the lowest cost for decision-making in the road-wood extraction binomial in a whole tree system in areas of forests planted with eucalyptus.

The bad dimensioning of the forest road network results in an excess of forest roads, identified through the optimal forest road density, allowing a significant reduction of the total cost for the implementation of forest roads.

Among the total costs, the costs demanded with the reconstruction of forest roads are the ones that impact the most, representing 70.6% of these costs. However, these were considered acceptable for low-volume roads.

The correct dimensioning of the optimal forest road density provides a cost reduction of 47.0%, with road construction, reconstruction, and maintenance. In addition, it allows for the detection of optimal points of productivity of the grapple skidder, wood extraction costs, and loss of the productive area, since these variables help in the planning and feasibility of the operation.

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