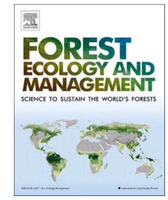
Forest Ecology and Management 549 (2023) 121265

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



Integrated planning of forest exploration infrastructures in an amazonian sustainable forest management area

Marcelo Otone Aguiar [a,*], Gilson Fernandes da Silva [a], Geraldo Regis Mauri [a], Adriano Ribeiro de Mendonça [a], Evandro Ferreira da Silva [b], Evandro Orfano Figueiredo [c], Jeferson Pereira Martins Silva [a], Valéria Alves da Silva [a], Rodrigo Freitas Silva [a], Gabriel Lessa Lavagnoli [a]

[a] *Federal University of Espirito Santo/UFES, Department of Forestry and Wood Science, Avenue Governor Lindemberg, 316, 29550-000, Jeronimo Monteiro, ES, Brazil*
[b] *Federal University of Pará/UFPA, University Campus of Altamira, Street Cel. José Porfírio, 2515, São Sebastião, 68372-040, Altamira, PA, Brazil*
[c] *Brazilian Agricultural Research Corporation (EMBRAPA-Acre), Rodovia BR-364, Km 14, 69900-970, Rio Branco, AC, Brazil*

ARTICLE INFO

Keywords:
Metaheuristics
Forest exploration infrastructures
Geographic information system
Tropical forest
Optimized planning

ABSTRACT

Planning the allocation of infrastructure exploration in native forests plays an important role in reducing costs and environmental damage. Traditionally, companies manually plan the infrastructure for exploration, which requires a lot of time and effort and implies low planning precision. Additionally, it makes it impossible for decision-makers to explore different scenarios and plan such structures in an integrated way. This research aims to evaluate two strategies that combine computational techniques for allocating the necessary exploration infrastructures in native forests. The study area was a native forest under a sustainable management regime located in the Brazilian Amazon. Three instances were formulated for resolution. Both employed strategies use exact and approximate methods for allocating infrastructures. The results indicate that the location of yards directly influences the optimization of road allocation and skid trails. However, it is essential that the manager evaluates several scenarios considering different numbers of yards to make the decision. It was also concluded that integrated planning makes it possible to obtain better results, as it allows for the choice of planning based on the best global solution by combining the set of infrastructures.

1. Introduction

Among logging activities legally approved in SFMP (Sustainable Forest Management Plan), the construction of exploitation infrastructures is one that causes the greatest environmental impact, generating areas degraded by tree cutting, landfilling, deforested land, forest fragmentation, and others (Ezzati et al., 2015; Holmes et al., 2002; Silva et al., 2018). Exploration infrastructures include the definition of main roads, access roads, storage yards, skidding trails, among others. They are necessary for the infrastructure plan included in micro-planning. The construction of infrastructures under Sustainable Forest Management (SFM) involves specific factors, such as prolonged periods of intense rain, the presence of swamps, permanent preservation areas (PPA), legally protected trees, and harvesting in a polycyclic system, commonly adopted in low-impact management, which can result in low revenue and, thus, limit investments (Akay, 2006; Epstein et al., 2006; Graetz et al., 2007; Silva et al., 2018).

Although these infrastructures are recognized, their definition is complex due to the diversity of species, tree sizes, different forest types, patterns of species distribution, soil types, terrain relief, hydrography, and other factors (Braz et al., 2005; Epstein et al., 2006; Figueiredo et al., 2007). Efforts can be found in the literature to optimize the layout of forest roads (Arima et al., 2008; Picard et al., 2006; Walker et al., 2013), optimize the allocation of storage yards (Contreras and Chung, 2007; Philippart et al., 2012; Silva et al., 2018, Silva et al., 2020), and, ultimately, optimize the layout of skid trails (Ezzati et al., 2015; Søvde et al., 2013; Sterenczak and Moskalik, 2015).

Considering the feasibility of carrying out optimized exploration infrastructure planning (Contreras and Chung, 2007; Philippart et al., 2012; Silva et al., 2020), Aguiar et al. (2020) evaluated the application

* Corresponding author.
E-mail addresses: marcelo.aguiar@ufes.br (M. Otone Aguiar), geraldo.mauri@ufes.br (G. Regis Mauri), adriano.mendonca@ufes.br (A. Ribeiro de Mendonça), evandrofs@ufpa.com (E. Ferreira da Silva), evandro.figueiredo@embrapa.br (E. Orfano Figueiredo), valeria.silva@ufes.br (V. Alves da Silva), rodrigo.f.silva@ufes.br (R. Freitas Silva), gabriel.lavagnoli@ufes.br (G. Lessa Lavagnoli).

https://doi.org/10.1016/j.foreco.2023.121265
Received 2 April 2023; Received in revised form 5 July 2023; Accepted 9 July 2023

of approximate algorithms for optimizing the allocation of storage yards in native forests. The metaheuristics Tabu Search, Variable Neighborhood Search, Greedy Randomized Adaptive Search Procedure, and Simulated Annealing (SA) were applied to the allocation storage yards using the p-median problem to minimize the distances between trees and the storage yards. The authors concluded that among the evaluated metaheuristics, the SA algorithm (Kirkpatrick et al., 1983) was the most efficient for the problem.

In another study, Aguiar et al. (2021) applied shortest path algorithms for planning the allocation of forest roads. In this case, the shortest path algorithms Bellman-Ford, Dijkstra, Dijkstra-OD, Dial, and D'Esopo-Pape were used to minimize distances from forest roads and damage to remaining forest. The algorithms took into consideration the slope of the land, PPA and areas susceptible to water ponding. The algorithm that consistently yielded the best time results across all evaluated scenarios was D'Esopo-Pape (Pape, 1974).

The studies presented above considered ecological and spatial aspects such as the presence of PPA, selective cutting, terrain slope, and others. However, they were limited to evaluating the allocation of yards (Aguiar et al., 2020) and the layout of forest roads (Aguiar et al., 2021) separately. Considering the importance of these components for planning exploration in native forests (Contreras and Chung, 2007; Silva et al., 2018; Søvde et al., 2013), in this work, we present a computational model that utilizes optimization algorithms to allocate infrastructures that enable forest exploration in an integrated way. Finally, we evaluated two allocation strategies that combine forest roads, storage yards, and skid trails to achieve an integration of these infrastructures while minimizing costs and damage to the remaining forest. To minimize these two variables, the algorithms take into consideration distance, PPA, remaining trees, slope of the land, and the risk of water ponding.

2. Methodology

To propose a methodology for integrating infrastructure planning, a sequence of steps was carried out aiming to combine the planning of allocation storage yards, forest roads layout, and skidding trails, and to evaluate two valid strategies for this combination. The methodological scheme (Fig. 1) represents necessary steps for development of present research.

2.1. Step 1: Building database

In this study, an area known as Forest Management Unit (FMU) 1A, which spans 26,897.96 ha, was utilized. It is located at geographic coordinates 1°45′23′' S and 56°34′21′' W in the municipalities of Terra Santa and Oriximiná, Pará State. This area belongs to Saracá-Taquera National Forest (NAFO). FMU 1A was granted to the company EBATA Produtos Florestais through a forest concession, competition No. 02/2012, organized by the Brazilian Forest Service, in accordance with the provisions of Law No. 11.284/2006 and Decree No. 6.063/2007. The study application area falls within the APU (Annual Planning Unit) 04/2018, specifically in PU (Production Units) 03, 04, and 05 (Fig. 2).

A graph was constructed for each PU used in this study. To achieve this, a geographic information system (GIS) was employed, utilizing a uniform distribution of equidistant vertices at 10 m. This approach facilitated a more precise adjustment in the layout of roads and trails, as

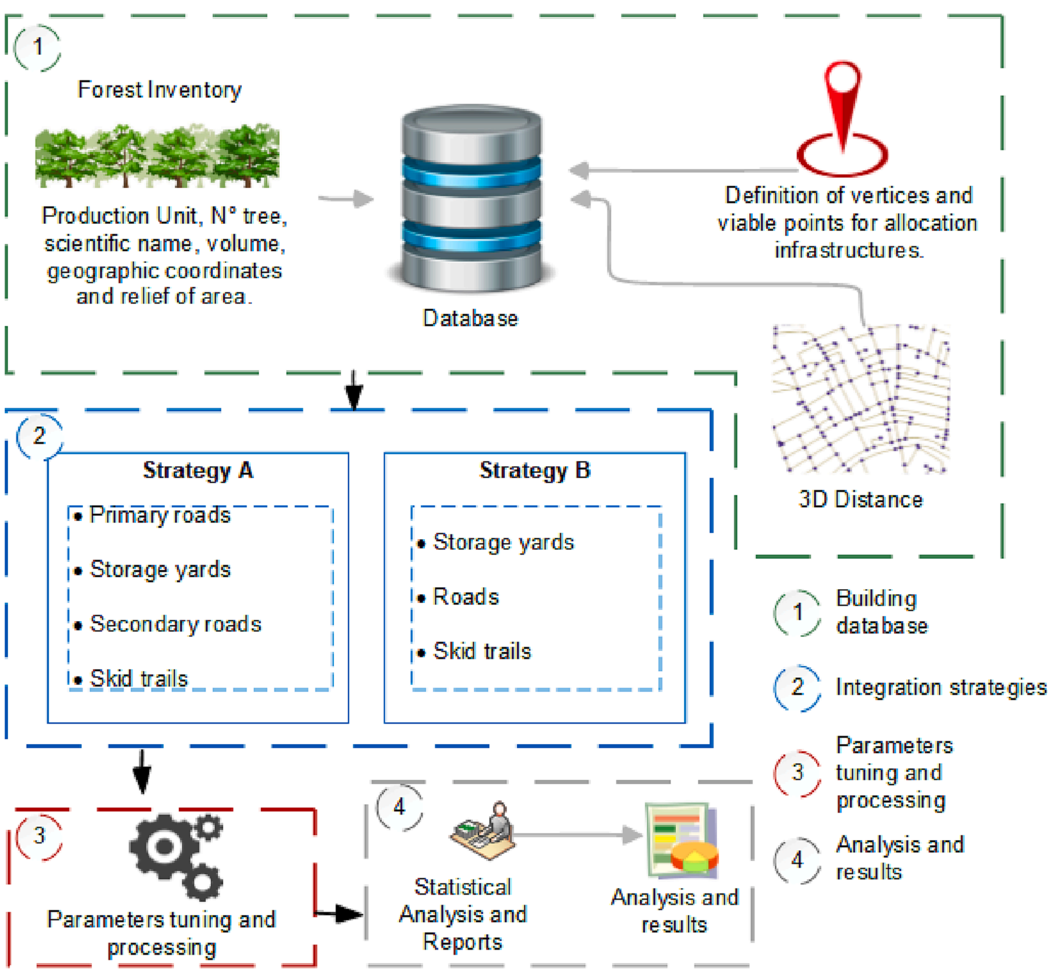


Fig. 1. Methodological flowchart for integration of forest exploitation infrastructure planning.

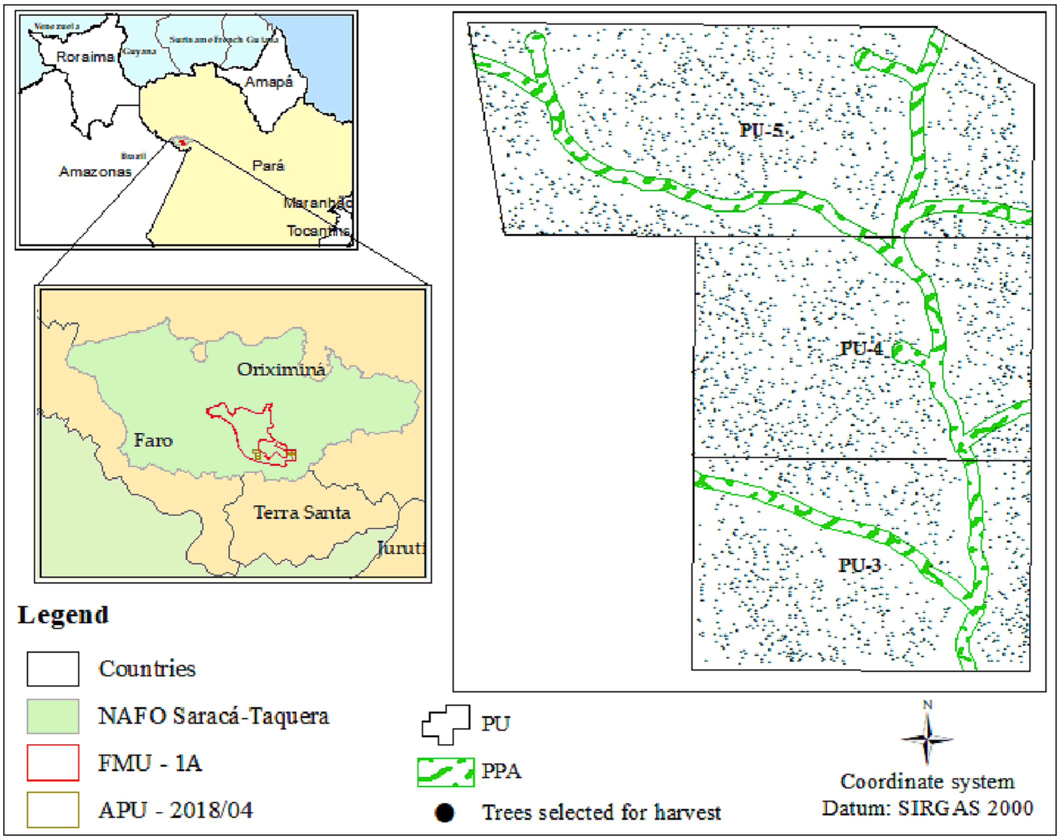


Fig. 2. Study area.

indicated by the results obtained in Aguiar et al. (2021). Information from the forest inventory was obtained for commercial trees, remaining trees, river sources, and PPA. This information is essential for determining unsuitable and favorable areas for infrastructure allocation.

The production units PU-3, PU-4, and PU-5 from FMU-1A were utilized to form three instances (Table 1). The combination of production units to form the instances had two objectives: first, to demonstrate the feasibility of conducting planning at the APU level (large areas); and second, to create larger instances to evaluate the performance of the implemented methods.

To plan the allocation of infrastructure in the study area, a computer program was developed using the ISO/IEC 9899:2011 language standard. The first step of the program performs a pre-processing (Fig. 3) with the purpose of: importing graph data, importing forest inventory data (including remaining law-protected trees and PPAs), importing land relief data, calculating distances between vertices of the graph and their neighbors, importing yard data and calculating distances between viable storage yard locations and exploitable trees, and cross-referencing information of the graph's vertices and edges with the forest inventory data.

The initial pre-processing steps (Fig. 3) are responsible for importing the following data: graph data (line 1), forest inventory data (line 2), river source data (line 3), and PPA data (line 4). Subsequently, relief data for the area, including slope of the land and areas susceptible to water ponding, is imported (line 5). Following that, points indicating the beginning and end of the road layout to be planned are imported (line 6). The subsequent step involves constructing a data structure graph based on the imported vertices and the distances between them (lines 7 and 8).

The *insertAreaEdge*() function is based on the distance between vertices to determine which vertices are neighboring vertices of vertex *i*. For each vertex identified as a neighbor of *i*, a connecting edge is created between the two vertices. To calculate the distance, a three-dimensional distance was utilized, following the methodology used by Aguiar et al. (2021). This distance takes into account the altitude, which enables obtaining greater precision when calculating the distance between two points, considering that terrains typically have varying degrees of slope. Consequently, when determining the shortest path, the method will naturally avoid areas with steep slopes, as the distance in these cases will be greater.

In the process of modeling the layout of forest roads, the same start and end points were utilized, in accordance with the planning conducted by EBATA, as illustrated in Table 2.

Table 1
Summary of instances formed from production units for infrastructure allocation planning.

Data	Instances		
	1	2	3
Productions Unit	PU-3	PU-3 PU-4	PU-3 PU-4 PU-5
Exploitable trees	820	1,864	3,172
Remnant trees	559	1,353	2,424
River Source	0	1	3
Area size (ha)	160	328	580.54
PPA size (ha)	15.13	26.68	53.57
Total vertices*	16,000	32,800	58,050
Total edges*	126,444	260,214	461,058

* In graph theory, vertices are nodes and edges are connections between vertices.

2.2. Step 2: Integration strategies

Traditionally, companies involved in the legal exploitation of native forests adopt a systematic arrangement where they initially establish primary roads in straight lines. Subsequently, secondary roads, also in

```
ar ← importGraphInstance(arFile)
tree ← importForestInventoryInstance(treeFile)
riverSource ← importRiverSourceInstance(srFile)
ppa ← importPPAInstance(ppaFile)
slope ← importReliefInstance(slopeFile)
roads ← importPlannedRoads(roadsFile)
gr ← buildGraph(ar)
insertAreaEdge(gr, tree, riverSource, ppa, slope)
```

Fig. 3. Pseudocode of infrastructure allocation preprocessing.

Table 2
Start and end points adopted in the planning of primary roads by EBATA.

PU	Geographic positioning			Length (m)
	Road stretch	Start	End	
PU-3	1	1°49′51.913″S 56°33′9.884″W	1°49′19.672″S 56°33′17.660″W	1,495.15
	2	1°49′44.091″S 56°32′45.610″W	1°49′44.092″S 56°32′49.494″W	
	3	1°49′28.458″S 56°32′45.614″W	1°49′28.459″S 56°32′49.498″W	
PU-3; PU-4	1	1°49′51.913″S 56°33′9.884″W	1°48′45.477″S 56°33′26.408″W	3,074.39
	2	1°49′44.091″S 56°32′45.610″W	1°49′44.092″S 56°32′49.494″W	
	3	1°49′28.458″S 56°32′45.614″W	1°49′28.459″S 56°32′49.498″W	
	4	1°49′3.054″S 56°32′45.620″W	1°49′3.056″S 56°32′53.388″W	
PU-3; PU-4; PU-5	1	1°49′51.913″S 56°33′9.884″W	1°48′35.710″S 56°33′42.012″W	4,177.07
	2	1°49′44.091″S 56°32′45.610″W	1°49′44.092″S 56°32′49.494″W	
	3	1°49′28.458″S 56°32′45.614″W	1°49′28.459″S 56°32′49.498″W	
	4	1°49′3.054″S 56°32′45.620″W	1°49′3.056″S 56°32′53.388″W	
	5	1°48′34.719″S 56°32′45.693″W	1°48′34.721″S 56°32′53.462″W	

Note: Geographic coordinates and lengths were obtained using a GIS (Geographic Information System).

straight lines, and storage yards are allocated along these roads. However, this arrangement does not necessarily promote the optimal cost-to-benefit-to-environmental-impact ratio (Amaral et al., 1998; Figueiredo et al., 2007; Silva et al., 2018).

In this study, two strategies were adopted to determine the exploitation infrastructures in the native forest. In the first strategy (Fig. 4a), primary roads are first defined, followed by the allocation of yards, and then the secondary roads are planned based on the locations of the primary roads and yards. Finally, trails are determined by considering the positions of the storage yards and exploitable trees. In the second strategy (Fig. 4b), the locations of the yards are initially defined. Based on the location of the storage yards and access roads to the production units (PUs), the roads are then determined, including primary and secondary roads. Additionally, the trails are defined, taking into account the positions of the storage yards and exploitable trees. The methodology for the two strategies was described in sections 2.2.1 and 2.2.2.

2.2.1. *Strategy A for defining infrastructure*

For strategy A, a heuristic was developed to assess all the start and end points for primary roads. It invokes the shortest path algorithm, which is responsible for determining the optimal route, following the methodology described in Aguiar et al. (2021). The D'Esopo-Pape algorithm was employed due to the favorable results reported in that study. Next, our heuristic applies the SA algorithm, which is responsible for optimizing the location of storage yards. The SA metaheuristic was employed with the p-median problem to minimize the distances between the trees and the storage yards. The objective was to minimize skidding distances. The SA algorithm utilized the same parameters as those employed in Aguiar et al. (2020), with a starting temperature of 1,000, a cooling rate of 0.985, and a freezing temperature of 0.001. The SA algorithm terminated when the freezing temperature was reached. For more comprehensive information on the methodology, refer to Aguiar et al. (2020).

The subsequent step entails determining the layout of secondary roads, for which the shortest path algorithm was also utilized, as described in Aguiar et al. (2021). The strategy adopted for connecting secondary roads between primary roads and storage yards was to always link the two closest points. This applies to connections between road segments and yards, as well as between yards themselves.

After identifying the closest points, the D'Esopo-Pape algorithm is utilized to determine the shortest paths. To integrate the application of the shortest path algorithm with the determination of connection points between storage yards and primary or secondary roads, a Secondary Road Connection Heuristic (SRCH) was developed (Fig. 5).

As illustrated in the pseudocode (Fig. 5), the SRCH algorithm explores all allocated yards (line 2). In each iteration, it calculates the distances between the evaluated yard and the closest points on the primary road, storage yard, and secondary road (lines 3–5). Next, the algorithm evaluates which of these points is the closest and establishes the connection accordingly (lines 7–12). If a yard has already been linked to another yard, the algorithm updates the links between yards (line 13) to avoid duplicating connections between already connected yards. Finally, the algorithm updates the secondary roads (line 15), considering the road that has just been defined as a potential connection point for the remaining yards.

The final step entails determining the layout of primary skid trails. Following the methodology described in section 2.2.3, points with the highest density of trees are initially identified, considering the minimum required number of primary trails. Subsequently, a method is applied to obtain an optimal route for the skid trails.

2.2.2. *Strategy B for defining infrastructure*

In Strategy B, the first step was the selection of storage yards using the SA metaheuristic to minimize the distances between trees and yards. The same parameters used in Strategy A were adopted for SA in Strategy B. For more details on the methodology, please refer to Aguiar et al. (2020). The next step is to determine the layout of primary and secondary roads based on the location of PU access points (Table 2) and the storage yards defined in the previous step. The D'Esopo-Pape algorithm was employed as described in Aguiar et al. (2021). Finally, skid trails are defined according to the methodology described in Section 2.2.3.

In this strategy, the type of road, whether primary or secondary, is determined based on the connection between sections. Roads connected to the access road are classified as primary, while roads connected to

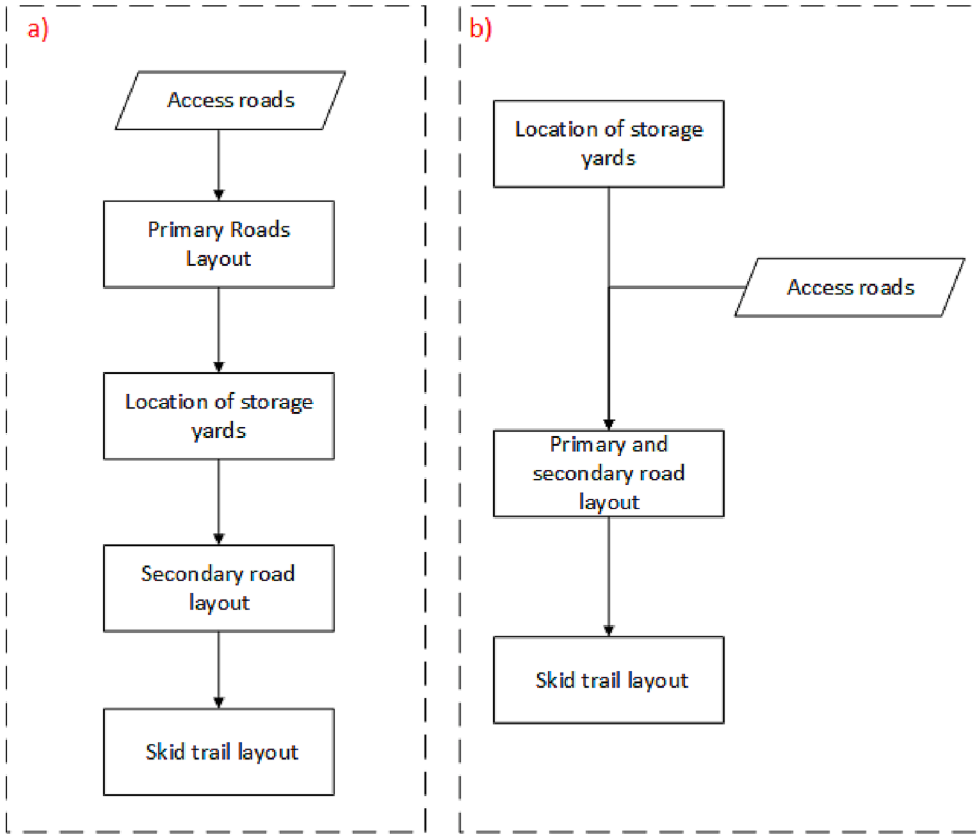


Fig. 4. Strategies adopted to determine the infrastructures in an integrated manner.

```
1  SRCH(area, yards)
2    for yard ∊ yards do
3      priRoadDist ← searchNearbyPrimaryRoad(yard)
4      secRoadDist ← searchNearbySecondaryRoad(yard)
5      yardDist ← searchNearbyYard(yard)
6      if priRoadDist <> 0 and secRoadDist <> 0 then
7        if priRoadDist < secRoadDist and priRoadDist < yardDist then
8          sol ← ShortestPath(area, yard, primaryRoad)
9        else if secRoadDist < priRoadDist and secRoadDist < yardDist then
10         sol ← ShortestPath(area, yard, secondaryRoad)
11       else
12         sol ← ShortestPath(area, yard, nearestYard)
13         updateYardConnections(yard, sol)
14       end if
15       updateSecondaryRoads(sol)
16     end if
17   end for
18 return sol
```

Fig. 5. Secondary road connection heuristics (SRCH).

primary roads are classified as secondary.

The strategy adopted is to connect the two closest points, whether it is between an access point and a storage yard, a road (primary or secondary) and a yard, or between two yards. Additionally, when connecting to a road, ensuring the flow of wood transport is taken into consideration. To implement these strategies, a heuristic was developed to establish connections between roads and yards, following the pseudocode outlined in Fig. 6.

According to the presented pseudocode (Fig. 6), the heuristic called Yard Linkage Heuristic (SYLH) requires the following input parameters: a solution containing the storage yards, and a graph with vertices and edges representing the area and the road entry/exit points for accessing that area of the PU. To obtain the layout, SYLH goes through all the storage yards (lines 2–18) and for each yard, it performs the following procedures: it obtains the closest access point to the yard and calculates the distance to it (line 3); gets the closest existing road point to the yard that meets the runoff flow and distance to it (line 4); checks if the distance to the access point or to the nearest road is different from zero (line

```
1  SYLH(area, yards, accessRoads)
2    for yard ∊ yards do
3      accessRoad ← searchNearbyAccess(yard, accessRoadDist, accessRoads)
4      existingRoad ← searchNearbyExistingRoad(yard, roadDist)
5      if accessRoadDist <> 0 and roadDist <> 0 then
6        nearbyYard ← searchNearbyYard(yard, yardDist)
7        if nearbyYard and yardDist < accessRoadDist and yardDist < roadDist then
8           sol ← ShortestPath(area, yard, nearbyYard)
9           establishForbiddenConnection(yard, nearbyYard)
10       else if accessRoadDist < roadDist and accessRoadDist < yardDist then
11          sol ← ShortestPath(area, yard, accessRoad)
12       else
13          sol ← ShortestPath(area, yard, existingRoad)
14       end if
15       updateExistingRoad(sol)
16       allSol.append(sol)
17     end if
18   end for
19   exitYardPU ← searchNearbyYard(accessRoads, yardDist)
20   sol ← ShortestPath(area, exitYardPU, accessRoads)
21   allSol.append(sol)
22   defineRoadType(allSol)
23   return allSol
```

Fig. 6. Storage yard linkage heuristics (SYLH).

5), as if not, the yard is located at a point where a road already exists and a stretch of road is not required for it.

If the distance to the nearest access point or road is different from zero, SYLH proceeds to search for the yard closest to the current yard (line 6). In this search, the criterion is that the distance from the closest yard to the access point, which is closest to the current yard, must be less than the distance from the current yard to its closest access point. This criterion ensures that the routes are always aligned with the runoff flow. Consequently, the prioritized factor is the technical consideration, which is crucial for the feasibility of management, rather than solely minimizing the length of the stretch. This means that a yard closer to an access point may be disregarded if it is located in a position that would make it impossible to guarantee the runoff flow.

Next, the SYLH checks if a nearby yard exists and if the distance to it is less than the distance from the current yard to the nearest access point and road section (line 7). If this condition is met, the D'Esopo-Pape algorithm is utilized to obtain a solution with the shortest path (line 8), ensuring that the Sustainable Forest Management (SFM) requirements between the current yard and the nearest yard are fulfilled. Finally, a prohibited connection is established between these yards (line 9), preventing SYLH from creating a duplicate link between them when evaluating the yard considered as the closest.

If the condition (line 7) is false, then SYLH proceeds to check if the closest point to the current yard is an access point within the area (line 10). If this condition is satisfied, the D'Esopo-Pape algorithm is used to obtain the shortest path solution (line 11) between the current storage yard and the closest access point. If neither of these two validations is true, it implies that the yard is closer to an existing stretch of road. In such a case, the shortest path algorithm is triggered to establish a connection between the yard and the road (line 13). Once the road layout is defined, the set of existing roads is updated (line 15) to include the newly added section, allowing it to be considered as a connecting section in the next iteration.

The solution obtained from the previous steps is then added to a solution set (line 16), which aims to store all the solutions generated by SYLH. Once the analysis of all yards is completed, SYLH identifies the yard closest to the PU exit point (line 19) and generates a final solution using the shortest path algorithm between the closest yard and the PU exit (line 20). The second-to-last step involves activating a function responsible for evaluating the flow of runoff on the roads and determining which sections will be designated as primary and secondary roads (line 22). Finally, at the end of the process, the solution containing all the roads is returned (line 23).

2.2.3. Skid trail layout definition

A three-step strategy was employed to obtain the layout of primary trails. The first step entails delineating the area of the storage yard by removing the portion encompassing the most distant trees. This is illustrated by the dashed line in Fig. 7.

After defining the storage yard area, the second stage begins with the application of the SA algorithm to the location problem, aiming to identify the minimum number of primary trails that need to be opened. The objective of this step is to identify points with the highest density of trees by minimizing the distances between them. To determine the minimum number of trails, the total number of trees associated with the storage yard is divided by 15, as recommended in reduced impact exploration guidelines (Amaral et al., 1998; FFT, 2002; Pinard et al., 1995). Once the points with the highest density of trees are determined, the third stage commences by utilizing the shortest path algorithm to connect the storage yard to these identified points from the second stage.

The shortest path algorithm employed in the third stage focuses solely on the deviation of trees, while other variables can be disregarded. This is because, as a result of the delimiting process, the vertices of the PPA are not included within the storage yard area. Additionally, in the study area adopted for this research, there are no areas with inclinations greater than 45°. Therefore, all areas within the study site are eligible for the opening of skid trails, and since these trails are temporary, there is no need to avoid areas prone to water ponding. To execute the three steps described, a heuristic was developed based on the pseudocode presented in Fig. 8.

As depicted in Fig. 8, the heuristic used to determine the layout of skid trails (HSTL) follows a step-by-step procedure. It starts by iterating

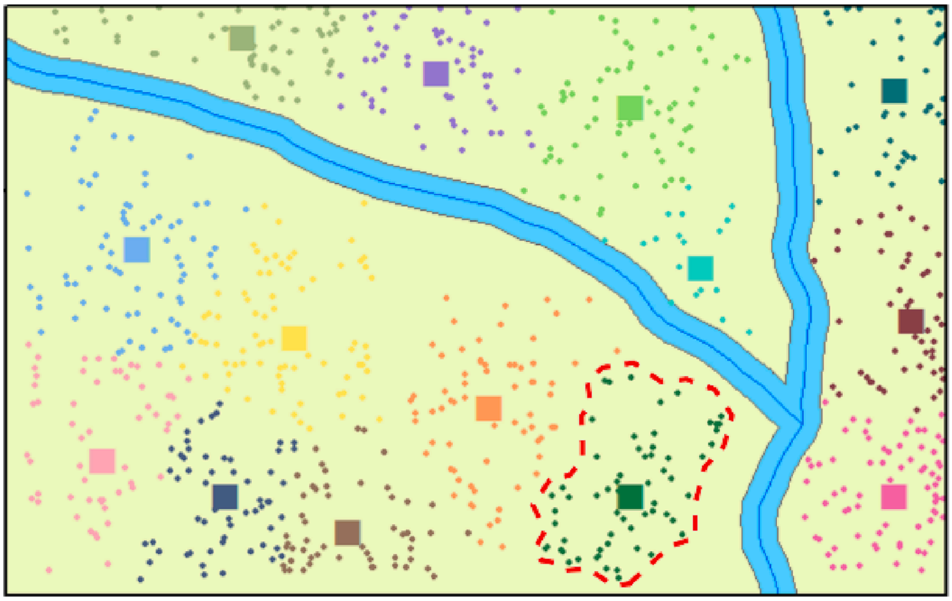


Fig. 7. Example of the delimitation of the storage yard area.

```
1 HSTL(yards, yardsTrees)
2   for yard ∈ yards do
3     yardArea ← searchYardArea(yard, yardsTrees)
4     solPTTrails ← constructiveHeuristic(yardArea, numberTrails)
5     solPTTrails ← simulatedAnnealing(solPTTrails, yardArea, numberTrails)
6     solTrails ← trailsHeuristic(yardArea, solPTTrails, numberTrails)
7   end for
8   return solTrails
```

Fig. 8. Heuristic Pseudocode for Skid Trail Layout (HSTL).

through all the yards (line 2) and for each yard, it calculates the area based on the associated trees (line 3). Once the yard area is obtained, the constructive heuristic is applied (line 4) to generate an initial solution by determining the location points for the skid trails in areas with higher tree density. Subsequently, the SA algorithm is executed (line 5) to further refine the solution generated by the constructive heuristic. In the final step, the function responsible for determining the trail layout examines the points obtained from the SA algorithm (line 6). Similar to other heuristics developed for road layout, this function is responsible for establishing connections between the skid trail and the yard or the closest existing trail.

2.3. Step 3: Parameters tuning

During the process of defining the layout of skid trails, constructive heuristics and the SA algorithm, both approximate methods, were employed to determine the locations of points with higher tree density within the yard. To optimize the performance of the SA algorithm, parameter tuning was conducted. A methodology based on the one presented in Aguiar et al. (2020) was utilized for this purpose.

The parameters were tuned using instance 1 - PU-3, where specific ranges of values were defined. The SA *meta*-heuristic was executed five times for each possible combination of these parameters, and the combination that yielded the best average objective function result was selected. The parameters that were tuned included the start temperature, neighborhood iterations, and cooling rate. To generate the initial solution, the Random Constructive Heuristic (RCH) was employed. This heuristic requires an input parameter, which is the number of iterations used to obtain the initial solution. The best values obtained from the tuning of the SA parameters are presented in Table 3.

2.4. Step 4: Analysis and results

The density of forest roads and skid trails is influenced by the placement of storage yards, as the yards and trees serve as references for determining their locations. Consequently, achieving an optimal density of forest roads is not a straightforward task, as several factors can impact the outcome. For instance, a larger number of storage yards leads to a reduced length of skid trails. However, the opposite effect is observed for secondary roads, where an increased number of storage yards tends to result in a greater extent of secondary road.

To evaluate the sensitivity of road layout strategies to changes in yard configuration, three scenarios were established for each instance. In these scenarios, the number of yards initially defined (as shown in Table 4) was altered. The changes made were significant, involving an

Table 3
SA input parameters for problem of locating the best points for primary trails layout.

Parameter	Range	Value
Start temperature	[1; 5; 10]	10
Freezing temperature	–	0.1
Cooling rate	[0.90; 0.95; 0.99]	0.99
Neighborhood Iterations	[30; 40; 50]	50
Initial solution method	–	RCH
No. of iterations for the initial solution	–	20,000

Table 4
Storage yard allocation processing parameters for 3 instances.

Parameter	Instance 1	Instance 2	Instance 3
Area (ha)	160	328	580.54
Number of trees	820	1,864	3,172
Total volume (m3)	3,600.61	7,563.64	11,949.85
Number of storage yards facilities	1,666	3,471	5,947
Amount of yard to be allocated	14	25	46
Storage yard capacity (m3)	257.19	302.55	259.78
Capacity flexibility (%)	10	10	10
Maximum distance of extraction (m)	379.45	379.45	379.45
Penalized objective function	1,000	1,000	1,000

increase or decrease of 50% in the total number of yards allocated for each instance, as indicated in Table 5.

To obtain feasible solutions, adjustments were made to the capacity values of the yards in terms of volume and maximum extraction distance. A 50% increase and decrease in these values were applied, except for scenario 3. In scenario 3, the maximum distance was set according to the guidelines provided by Silva et al. (2018b), as a 50% decrease in distance proved to be excessively restrictive, resulting in unfeasible solutions.

Since the procedure used to determine the location of storage yards is an approximate method, each execution of the method can yield different results. To ensure a fair comparison between the two strategies, the procedures were performed together, utilizing the same solution obtained for the location of yards in each iteration. The determination of the best infrastructure allocation solution was based on minimizing the sum of the solutions for storage yards, roads, and trails. This approach allowed for a comprehensive evaluation by considering the overall performance of the strategies.

The computational results for the allocation of storage yards were analyzed based on the best solution found for each instance and scenario. The following metrics were considered: the value of the best solution found [Best Sol (m)], the average value of the objective function [Avg Sol (m)], the deviation of the solutions [Dev (%)], the computational processing time required to find the best solution [Time (mn)], the average time to obtain the best solution [Avg time (mn)], and the GAP (%). The means were calculated based on 30 runs. The deviation of solutions was calculated using Equation 1, following the methodology described in Aguiar et al. (2021).

$$Dev(\%) = \frac{Avg - Best}{Best} * 100$$

To evaluate the results of the length of planned skid trails, several metrics were considered for each instance and scenario. These metrics include the total length of skid trails [Total Length (m)], the density of skid trails [Density (m.ha-1)], the average density of skid trails across all solutions [Avg density (m.ha-1)], the objective function value of the best solution for skid trails [Best Sol (m)], and the time required to obtain the solution [Time (s)]. It is important to note that the results for storage yards and skid trails are common to both infrastructure allocation strategies, as the same yard allocation solution was used in both strategies. To assess the cost of building the infrastructure, including storage yards, primary roads, secondary roads, and skid trails, cost data from the study conducted by Silva (2019) were adapted and utilized.

Table 5
Parameters adopted for analyzing scenarios in allocation of infrastructure.

Instance	Scenario	Number of yards that must be allocated	Capacity of storage yards (m^3)	Maximum distance of extraction (m)
1	1	14	257.19	379
2		25	302.55	
3		46	259.78	
1	2	7	514.37	569
2		13	581.82	
3		23	519.56	
1	3	21	171.46	258
2		37	204.42	
3		69	173.19	

2.4.1. Analysis and results of strategies A and B

To evaluate the computational results of primary roads, the following metrics were considered for each instance and road segment: the length of the road segment [Length (m)], the total length of all road segments [Total length (m)], the density of roads [Density ($m.ha^{-1}$)], the objective function [Objective function] (which represents the length of the road segment affected by penalties from evaluated variables), the total objective function [Total objective function] (representing the sum of the objective function values for all road segments), and the processing time required to obtain the solution [Time (s)].

The evaluation of secondary roads considered the following metrics for each instance and scenario: the objective function for the solution of yards associated with roads [Yards objective function], the total length of secondary roads [Total length (m)], the density of secondary roads [Density ($m.ha^{-1}$)], the average density of all solutions obtained from secondary roads [Avg density ($m.ha^{-1}$)], the objective function of the best solution from secondary roads [Total objective function], and the time required to obtain the secondary road solution [Time (s)].

3. Results

3.1. Results obtained for strategy A

The results of the best solution for Strategy A are presented as follows. Next, the computational results for primary roads, storage yards, secondary roads, and trails are described.

3.1.1. Best solution

Table 6 presents a summary of the extent and density of the best solution for the scenarios evaluated in Strategy A. The results indicate a significant difference in the total density among the scenarios for three instances. For instance, in Scenario 2 of the first instance, the total density is 2.8% higher compared to Scenario 1, while Scenario 3 has a 5% lower total density than Scenario 1. It is worth noting that considering the smallest evaluated area of 160 ha, a difference exceeding 2% corresponds to a considerable size.

In general, Scenario 3 exhibited the lowest total density of roads and trails, as indicated in Table 6. This outcome was primarily influenced by the high number of yards in this scenario, which subsequently resulted in a lower density of skid trails.

By considering the recommended size of storage yards (Amaral et al., 1998) and the recommended width of road strips for forest exploration in native forests (Sessions et al., 2007), it is possible to calculate the impact of infrastructure construction in terms of the amount of deforested land, as shown in Table 7. In percentage terms, the total deforested land is lower in the second scenario for all instances. Conversely, the third scenario has a greater impact in terms of total deforested land, but a smaller impact in deforested land per skid trail. Therefore, although the third scenario resulted in a lower total density of roads and trails (Table 6), it has the greatest impact on the total deforested land (Table 7) due to the large number of storage yards.

The data in Table 7 was calculated based on the total area of the instances. The same calculation can be performed considering only the area of effective exploitation, as shown in Table 8. However, there is no difference in the area measured in hectares for the implementation of infrastructure, but only in the percentage of the area based on the area of effective exploitation. When considering only the area of effective management, the relative percentage of damage increases.

Regarding costs (Table 9), the results indicate a significant difference in total costs between the evaluated scenarios for the three instances. For instance, scenario 2 of instance 1 is 28.6% lower than scenario 1 and

Table 6
Summary for length and density of Strategy A roads and trails.

Instance	Infrastructure	Scenario 1		Scenario 2		Scenario 3	
		Length (m)	Density (m.ha^{-1})	Length (m)	Density (m.ha^{-1})	Length (m)	Density (m.ha^{-1})
1	Primary roads	1,475.67	9.22	1,475.67	9.22	1,475.67	9.22
	Secondary roads	2,724.40	17.03	1,600.93	10.01	3,613.46	22.58
	Skid trails	4,863.69	30.40	6,241.54	39.01	3,522.43	22.02
Total		9,063.76	56.65	9,318.14	58.24	8,611.55	53.82
2	Primary roads	3,027.68	9.23	3,027.68	9.23	3,027.68	9.23
	Secondary roads	5,148.21	15.70	3,303.47	10.07	7,427.43	22.64
	Skid trails	13,389.61	40.82	14,939.73	45.55	10,245.78	31.24
Total		21,565.50	65.75	21,270.87	64.85	20,700.88	63.11
3	Primary roads	3,696.02	6.37	3,696.02	6.37	3,696.02	6.37
	Secondary roads	12,407.66	21.37	6,926.44	11.93	15,995.27	27.55
	Skid trails	23,147.57	39.87	28,035.96	48.29	17,880.88	30.80
Total		39,251.24	67.61	38,658.42	66.59	37,572.16	64.72

Table 7
Impact of infrastructure in hectares of deforested land for implementing infrastructure in strategy A.

Instance	Scenario	Total area impact									
		Storage yards		Primary roads		Secondary roads		Skid trails		Total	
		ha	% of total	ha	% of total	ha	% of total	ha	% of total	ha	% of total
1	1	0.7	0.44	1.48	0.92	1.63	1.02	2.19	1.37	6.00	3.75
(160 ha)	2	0.35	0.22			0.96	0.60	2.81	1.76	5.59	3.50
	3	1.05	0.66			2.17	1.36	1.59	0.99	6.28	3.92
2	1	1.25	0.38	3.03	0.92	3.09	0.94	6.03	1.84	13.39	4.08
(328 ha)	2	0.65	0.20			1.98	0.60	6.72	2.05	12.38	3.78
	3	1.85	0.56			4.46	1.36	4.61	1.41	13.94	4.25
3	1	2.3	0.40	3.70	0.64	7.44	1.28	10.42	1.79	23.86	4.11
(580.54 ha)	2	1.15	0.20			4.16	0.72	12.62	2.17	21.62	3.72
	3	3.45	0.59			9.60	1.65	8.05	1.39	24.79	4.27

Table 8
Impact of infrastructure in percentage of deforested land for implementing infrastructure in strategy A based on effective exploitation area.

Instance	Scenario	Impact on effective exploration area (%)				
		Storage yards	Primary roads	Secondary roads	Skid trails	Total
1	1	0.48	1.02	1.13	1.51	4.14
(144.87	2	0.24		0.66	1.94	3.86
ha)	3	0.72		1.50	1.09	4.33
2	1	0.41	1.00	1.03	2.00	4.44
(301.32	2	0.22		0.66	2.23	4.11
ha)	3	0.61		1.48	1.53	4.63
3	1	0.44	0.70	1.41	1.98	4.53
(526.97	2	0.22		0.79	2.39	4.10
ha)	3	0.65		1.82	1.53	4.70

43.5% lower than scenario 3. The total cost of the second scenario is the lowest across all three instances because, although there is an increase in skid trails in this scenario, which have lower costs, there is a reduction in the number of storage yards and secondary roads, which have higher costs. These factors contribute to the second scenario resulting in the lowest cost among the three evaluated scenarios.

The results (Table 9) also indicate that the total cost of the third scenario was higher due to an increase in the number of yards and the density of secondary roads. Although the cost of skid trails is lower, this reduction was not sufficient to compensate for the increases in other costs. Additionally, the relationship between the costs of roads and trails can be observed, where primary roads, being wider, require a greater utilization of labor and machinery. Conversely, trails have lower costs because, in addition to having a smaller width, the soil is not scraped, resulting in lower demands for effort and operating time.

Fig. 9 presents the result of the best solution obtained for instance 3 in strategy A and the first scenario, considering ecological and spatial restrictions (hydrographic and topographic). The image showcases all the planned infrastructure, including 3,696.02 m of primary roads, 12,407.66 m of secondary roads, 23,147.57 m of primary skid trails, 46 storage yards, and 3,171 exploitable trees. It can be observed that the road layout effectively deviates from the inventoried trees, and the allocation of storage yards is concentrated in central areas near clusters of trees. Furthermore, it is evident that there are advantages to planning

Table 9
Construction cost of exploration infrastructures for strategy A.

Instance	Scenario	Infrastructure construction cost (BRL)				
		Storage yards	Primary roads	Secondary roads	Skid trails	Total
1	1	4,389.31	3,196.00	2,997.35	704.76	11,287.42
	2	2,194.66		1,761.32	904.42	8,056.39
	3	6,583.97		3,975.47	510.41	14,265.84
2	1	7,838.05	6,557.33	5,663.99	1,940.20	21,999.57
	2	4,075.79		3,634.42	2,164.82	16,432.36
	3	11,600.32		8,171.54	1,484.65	27,813.84
3	1	14,422.02	8,004.81	13,650.72	3,354.16	39,431.71
	2	7,211.01		7,620.37	4,062.50	26,898.69
	3	21,633.03		17,597.76	2,591.00	49,826.60

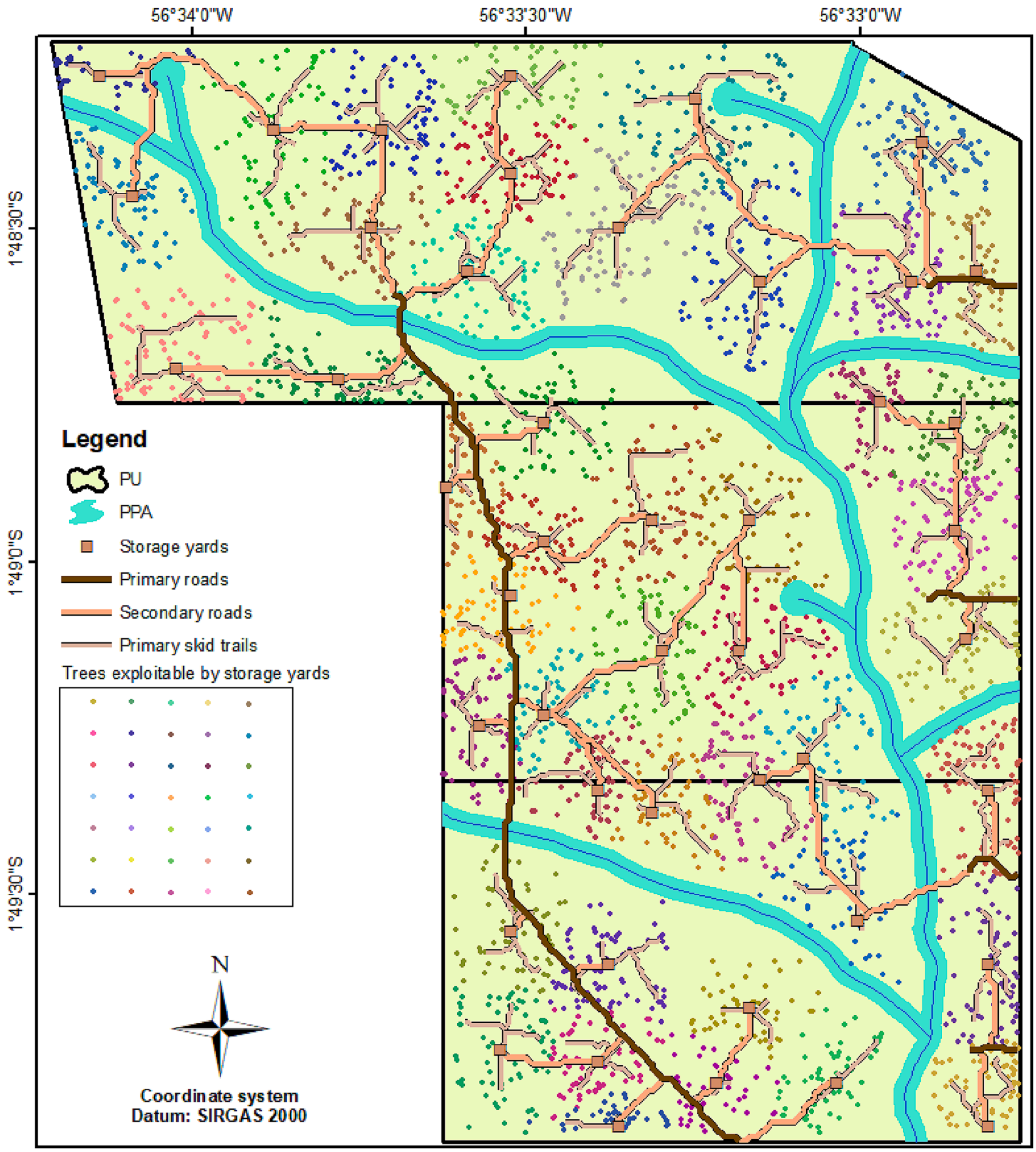


Fig. 9. Best solution obtained in strategy A considering ecological and spatial restrictions. The image allows observing deviations applied to inventoried trees, by method in instance 3 applied to first scenario.

the allocation of infrastructure by combining two or more Production Units (PUs), as the ends of these PUs are utilized for storage yards and roads. Moreover, the method proves to be efficient in minimizing the crossing of Permanent Preservation Areas (PPAs), with only five occurrences in the 580.54 ha evaluated area. This condition is feasible for the study area, considering that the watercourses are crossable.

In Fig. 10, the same solution obtained while considering ecological and spatial restrictions, such as deviations from obstacles, remaining trees, and Permanent Preservation Areas (PPAs), is presented. However, this figure specifically highlights deviations related to the slope of the terrain and areas at risk of water ponding.

Fig. 10a illustrates the deviation of areas with slopes exceeding the recommended level. The restriction was applied specifically to primary and secondary roads, as there are no areas with slopes exceeding 100%. The method avoided such areas in the infrastructure allocation. In Fig. 10b, the solution's capability to divert areas prone to water ponding is depicted. Similar to the previous case, the restriction was applied to primary and secondary roads. The method effectively favored areas with low to medium risk of water accumulation when allocating infrastructure. However, it is worth noting that there are still roads present in high-risk areas due to the necessity of serving storage yards located in those regions.

3.2. Computational results for strategy A

The computational results for primary roads, secondary roads, skid trails, and storage yards in strategy A are presented below. The results demonstrate the relationship between storage yard allocation and the objective function of roads and trails (Table 10). The variation in the number of storage yards has an impact on the objective function. In the

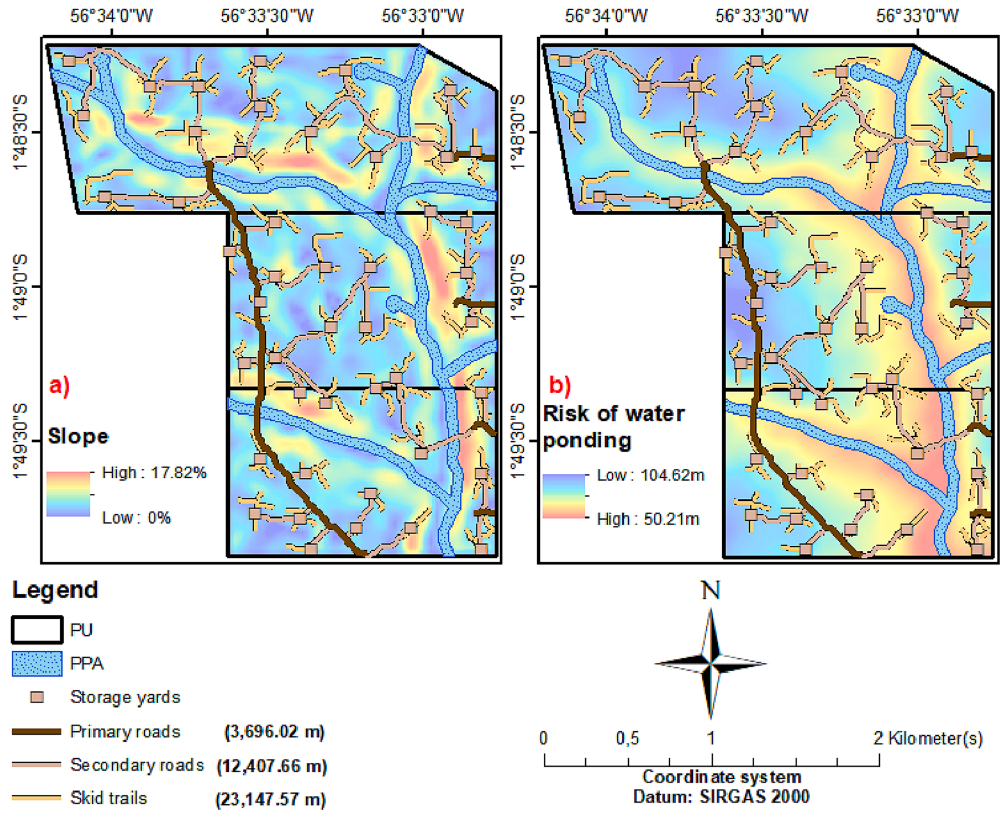


Fig. 10. Deviations from the best solution obtained in strategy A considering ecological and spatial restrictions for Instance 3 and the first scenario. The image allows for the observation of deviations applied to the slope of the terrain (a) and areas susceptible to water ponding (b).

second scenario, where the number of yards decreases, there is a reduction in the objective function of secondary roads and an increase in skid trails. Conversely, when the number of yards increases in the third scenario, the objective function of secondary roads increases while the distance to trees decreases. However, more roads are needed to serve the additional yards. The time required to obtain the solutions did not exceed 10 min for each scenario, which is reasonable for generating scenarios to be considered in decision-making. In all scenarios, the objective function exceeded the extension value, indicating that all solutions obtained were penalized due to the constraints evaluated in the problem.

Regarding the results obtained for the allocation of storage yards (Table 11), it can be observed that, in general, the deviations obtained were low, indicating that the SA method was robust. However, in instance 3, there was a higher deviation, suggesting that as the number of instance variables increased, the stability of the SA method in producing solutions was reduced. Nevertheless, for the instances where the deviation was low, it can be concluded that the SA method performed well and produced reliable results.

3.3. Results obtained for strategy B

3.3.1. Best solution

Table 12 presents a summary of the extent and density of the best solution for the scenario evaluated in strategy B. It can be observed that scenario 3 resulted in the lowest total density for all three instances. The difference in total density compared to scenario 1 was smaller for instance 1, with a reduction of 2.78%, and for instance 2, where the difference was insignificant compared to scenario 2. However, for instance 3, the difference in total density was 4.7% compared to scenario 1 and 2.5% compared to scenario 2.

In strategy B, the same reference data for storage yard size (Amaral et al., 1998) and road lane width (Sessions et al., 2007) were considered to assess the impact per deforested land. The results in Table 13 demonstrate that scenario 2 resulted in the smallest amount of deforested land for all three instances. However, it is important to note that this scenario also had the largest amount of deforested land for skid trails. Conversely, scenario 3 showed the opposite trend, with a larger amount of deforested land for skid trails and a smaller overall deforested land.

When considering only the area of effective exploration (Table 14), the total percentage of deforested land naturally increases, but the relationship between the three scenarios remains the same.

For strategy B, the cost data are shown in Table 15, where once again there is a considerable difference between the costs of the evaluated scenarios. For instance, in scenario 2 of instance 1, the total costs are 43.8% lower than scenario 1 and 50.3% lower than scenario 3.

Fig. 11 presents the result of the best solution obtained for instance 3 in strategy B and the first scenario, considering ecological and spatial (hydrographic and topographic) constraints.

The image (Fig. 11) includes all infrastructure planned by the method, including 2,846.95 m of primary roads, 13,202.96 m of secondary roads, 22,727.74 m of primary skid trails, 46 storage yards, and 3,171 exploitable trees. Similar to what occurred in strategy A, there is an advantage in planning the allocation of infrastructures by combining two or more PUs. This can be observed at the ends of these PUs where infrastructures such as storage yards and roads are utilized. In strategy A (Fig. 9), the planning resulted in five (5) crossings of permanent preservation areas (PPAs). Similarly, in strategy B, the number of PPA crossings is also five (5) within the 580.54 ha area. Once again, the crossing of PPAs is feasible for the area evaluated in this study as the watercourses are crossable.

The deviations from obstacles, such as remaining trees and PPAs, as well as the deviations from areas with a slope above the recommended level and areas susceptible to water ponding, can be observed in Fig. 12. In Fig. 12a, the deviation of slope areas above the recommended level is

Table 10
Computational results for roads and trails of strategy A.

Instance	Scenario	Yards objective function	Infrastructure	Length (m)	Density (m.ha^{-1})	Avg density (m.ha^{-1})	Objective function (m)
1	1	105,419.20	Primary	1,475.67	9.22	–	2,029.75
(160 ha)			Secondary	2,724.40	17.03	17.72	3,584.62
			Skid trails	4,863.69	30.40	33.40	5,117.85
			Total	9,063.76	56.65	Time Sol (s)	37,20
	2	154,697.90	Primary	1,475.67	9.22	–	2,029.75
			Secondary	1,600.93	10.01	10.14	2,444.52
			Skid trails	6,241.54	39.01	40.13	6,577.91
			Total	9,318.14	58.24	Time Sol (s)	79,33
	3	87,322.85	Primary	1,475.67	9.22	–	2,029.75
			Secondary	3,613.46	22.58	25.12	3,941.99
			Skid trails	3,522.43	22.02	23.23	3,879.14
			Total	8,611.56	53.82	Time Sol (s)	26,21
2	1	259,370.15	Primary	3,027.68	9.23	–	3,484.48
(328 ha)			Secondary	5,148.21	15.70	17.65	5,397.11
			Skid trails	13,389.61	40.82	40.73	14,402.42
			Total	21,565.5	65.75	Time Sol (s)	137,42
	2	359,614.27	Primary	3,027.68	9.23	–	3,484.48
			Secondary	3,303.47	10.07	10.21	4,250.28
			Skid trails	14,939.73	45.55	46.27	15,886.05
			Total	21,270.88	64.85	Time Sol (s)	240,31
	3	217,892.37	Primary	3,027.68	9.23	–	3,484.48
			Secondary	7,427.43	22.64	23.04	8,295.73
			Skid trails	10,245.78	31.24	32.39	11,326.73
			Total	20,700.89	63.11	Time Sol (s)	95,41
3	1	476,464.23	Primary	3,696.02	6.37	–	4,387.44
(580.54 ha)			Secondary	12,407.66	21.37	21.55	14,304.30
			Skid trails	23,147.57	39.87	39.55	24,964.61
			Total	39,251.25	67.61	Time Sol (s)	312,10
	2	735,908.86	Primary	3,696.02	6.37	–	4,387.44
			Secondary	6,926.44	11.93	12.91	8,553.98
			Skid trails	28,035.96	48.29	48.48	29,603.45
			Total	38,658.42	66.59	Time Sol (s)	603,67
	3	435,782.11	Primary	3,696.02	6.37	–	4,387.44
			Secondary	15,995.27	27.55	28.48	20,706.67
			Skid trails	17,880.88	30.80	31.86	19,197.07
			Total	37,572.17	64.72	Time Sol (s)	259,65

Table 11
Computational results for allocation of storage yards in three scenarios.

Instance	Scenario	Best Sol (m)	Avg Sol (m)	Dev (%)	Time (mn)	Avg time (mn)
1	1	104,653.59	105,322.66	0.64	24.02	14.58
	2	154,697.90	154,697.90	0.00	0.45	0.54
	3	87,220.58	88,036.59	0.94	17.38	17.70
2	1	257,845.01	259,779.59	0.75	9.81	16.39
	2	358,651.28	359,606.34	0.27	2.47	15.03
	3	215,089.28	217,383.28	1.07	9.82	17.81
3	1	460,307.60	471,996.58	2.54	12.30	20.07
	2	702,530.51	733,322.30	4.38	28.30	21.94
	3	420,270.18	474,174.35	12.83	21.93	23.40

depicted. The restriction was applied only to roads since there are no areas with a slope exceeding 100%. The image demonstrates the effectiveness of the method in avoiding such areas.

Fig. 12b shows the relationship between the solution and deviations in areas susceptible to water ponding, which were also applied only to roads. Similarly, it can be observed that the method, when allocating infrastructure, favored areas with low and medium risk, reaching high-risk areas only when necessary to serve the storage yards located in those areas.

The computational results for storage yards, roads, and trails from strategy B are presented below. Similar to the results observed in strategy A, in strategy B, the number of yards affects primary and secondary roads and trails, as can be seen in Table 16. However, the behavior observed in instance 1 was different than expected. Only for instances 2 and 3, there was a clear relationship between the reduction

Table 12
Summary for length and density of Strategy B roads and trails.

Instance	Infrastructure	Scenario 1		Scenario 2		Scenario 3	
		Length (m)	Density (m.ha^{-1})	Length (m)	Density (m.ha^{-1})	Length (m)	Density (m.ha^{-1})
1	Primary roads	2,753.67	17.21	992.06	6.20	1,306.87	8.17
	Secondary roads	1,101.95	6.89	1,504.29	9.40	3,601.82	22.51
	Skid trails	4,973.31	31.08	6,241.54	39.01	3,681.65	23.01
Total		8,828.93	55.18	8,737.89	54.61	8,590.34	53.69
2	Primary roads	1,454.83	4.44	1,432.13	4.37	1,880.41	5.73
	Secondary roads	7,008.16	21.37	3,969.82	12.10	8,296.42	25.29
	Skid trails	13,361.15	40.74	15,042.02	45.86	10,245.78	31.24
Total		21,824.14	66.54	20,443.97	62.33	20,422.62	62.26
3	Primary roads	2,846.95	4.90	2,948.76	5.08	2,284.47	3.94
	Secondary roads	13,202.96	22.74	6,921.67	11.92	16,180.88	27.87
	Skid trails	22,727.74	39.15	28,090.75	48.39	18,570.96	31.99
Total		38,777.64	66.80	37,961.18	65.39	37,036.32	63.80

Table 13
Impact of infrastructure on hectares of deforested land for implementing infrastructure in strategy B.

Instance	Scenario	Total area impact									
		Storage yards		Primary roads		Secondary roads		Skid trails		Total	
		ha	% of total	ha	% of total	ha	% of total	ha	% of total	ha	% of total
1	1	0.7	0.44	2.75	1.72	0.66	0.41	2.24	1.40	6.35	3.97
(160 ha)	2	0.35	0.22	0.99	0.62	0.90	0.56	2.81	1.76	5.05	3.16
	3	1.05	0.66	1.31	0.82	2.16	1.35	1.66	1.04	6.17	3.86
2	1	1.25	0.38	1.45	0.44	4.20	1.28	6.01	1.83	12.92	3.94
(328 ha)	2	0.65	0.20	1.43	0.44	2.38	0.73	6.77	2.06	11.23	3.42
	3	1.85	0.56	1.88	0.57	4.98	1.52	4.61	1.41	13.32	4.06
3	1	2.3	0.40	2.85	0.49	7.92	1.36	10.23	1.76	23.30	4.01
(580.54 ha)	2	1.15	0.20	2.95	0.51	4.15	0.72	12.64	2.18	20.89	3.60
	3	3.45	0.59	2.28	0.39	9.71	1.67	8.36	1.44	23.80	4.10

Table 14
Impact of infrastructure in percentage of effective exploration area for implementation infrastructure in strategy B.

Instance	Scenario	Impact on effective exploration area (%)				
		Storage yards	Primary roads	Secondary roads	Skid trails	Total
1	1	0.48	1.90	0.46	1.54	4.39
(144.87	2	0.24	0.68	0.62	1.94	3.49
ha)	3	0.72	0.90	1.49	1.14	4.26
2	1	0.41	0.48	1.40	2.00	4.29
(301.32	2	0.22	0.48	0.79	2.25	3.73
ha)	3	0.61	0.62	1.65	1.53	4.42
3	1	0.44	0.54	1.50	1.94	4.42
(526.97	2	0.22	0.56	0.79	2.40	3.96
ha)	3	0.65	0.43	1.84	1.59	4.52

of secondary roads and the increase of trails, and vice versa. When analyzing the objective function of yards and skid trails separately, it can be concluded that in all scenarios, the relationship was within the expected range.

3.4. Comparison between A and B strategies

To compare the plans obtained by strategies A and B, a summary was performed (Table 17) considering consolidated totals for storage yards, primary and secondary roads, and skid trails. The first aspect presented is the total length, in which only in scenario 1 of instance 2 did strategy A outperform strategy B.

The other aspects presented in Table 17, including density, deforested land, and cost, followed a similar trend to the first aspect, except for the cost aspect of strategy A in scenario 1 of the first and second instances.

4. Discussion

Based on our experiments, it is possible to observe the sensitivity of road and skid trail density to the number of storage yards in native forest exploitation. In all scenarios conducted for three instances in both strategies, the observed behavior was as expected. In the first scenario, the number of yards proposed in the planning by company EBATA was adopted, while in the second scenario, this number was reduced by 50%. Lastly, in the third scenario, a 50% increase was applied.

The reduction of storage yards resulted in a decrease in road density but an increase in trail density, as observed in the results of both implemented strategies (Table 6 and Table 12, respectively). Conversely, the third scenario demonstrated the opposite effect: an increase in the number of yards led to an increase in road density and a subsequent reduction in skid trail density.

Both methodologies proved to be effective in generating integrated infrastructure allocation plans while considering various constraints, such as maximum dragging distance, yard storage capacity, remaining trees, PPAs, slopes above recommended levels, and areas susceptible to water ponding. Furthermore, when strategies were applied to areas involving multiple production units (PUs), it was possible to optimize the utilization of infrastructures across PUs and minimize the need for crossing PPAs.

The presented images of the planning (Fig. 9 and Fig. 11) demonstrate the effectiveness of the methodologies in allocating infrastructures in areas with high density of exploitable trees. It is evident that the main skid trails were strategically placed to serve the entire cluster of trees associated with the storage yards, taking into account the limitation on the number of stems that can be dragged along the same trail (Amaral et al., 1998). Furthermore, it is notable that the storage yards were allocated at a sufficient distance from the PPAs to prevent the association of trees located on the other side of the PPA, considering that dragging stems through the PPA is prohibited (Pinard et al., 1995; Sist, 2000).

The planning images (Fig. 10 and Fig. 12) highlight the importance of treating deviation variables with penalties in order to determine the layout of roads in the SFM area. Without applying penalties, the number of restricted regions would be significant, making it difficult to obtain feasible solutions. For instance, in Fig. 10c, storage yards were allocated in an area with a risk of water ponding, and these yards are surrounded

Table 15
Construction cost of exploration infrastructures for strategy B.

Instance	Scenario	Infrastructure construction cost (BRL)				
		Storage yards	Primary roads	Secondary roads	Skid trails	Total
1	1	4,389.31	5,963.89	1,212.35	720.65	12,286.20
	2	2,194.66	2,148.59	1,655.00	904.42	6,902.67
	3	6,583.97	2,830.41	3,962.67	533.48	13,910.53
2	1	7,838.05	3,150.85	7,710.28	1,936.07	20,635.26
	2	4,075.79	3,101.70	4,367.54	2,179.64	13,724.66
	3	11,600.32	4,072.59	9,127.60	1,484.65	26,285.16
3	1	14,422.02	6,165.90	14,525.70	3,293.32	38,406.94
	2	7,211.01	6,386.41	7,615.12	4,070.44	25,282.98
	3	21,633.03	4,947.70	17,801.96	2,690.99	47,073.69

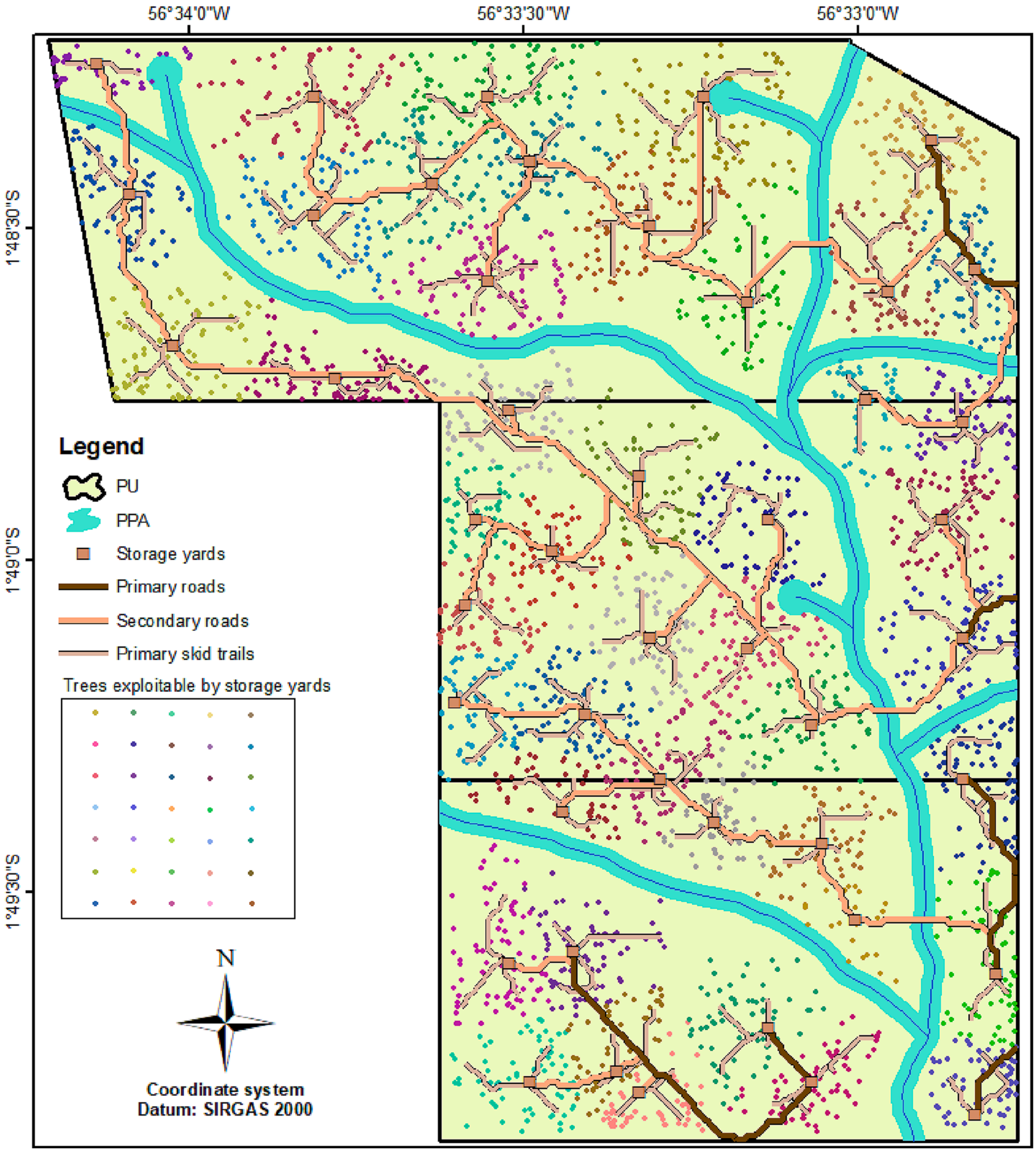


Fig. 11. Best solution obtained in strategy B considering ecological and spatial restrictions. The image allows for observing the deviations applied to inventoried trees by the method in instance 3 applied to the first scenario.

by such areas near the PPAs. If the restriction was handled by simply removing edges from the graph obtained for the area, these yards would not be accessible. Another example is the transposition of PPAs, which was necessary to serve yards that would not be reachable if the restriction was handled by excluding edges from the planning.

In general, the analyzed variables, namely extension, density, deforested land, and cost, demonstrate an advantage in scenario 2 for both evaluated strategies. This indicates that the number of allocated storage yards directly influences these factors, suggesting that planning with a lower number of yards may yield better results compared to the planning carried out by the company. However, it is important to note that this option may lead to increased costs associated with dragging the wood using skidders or similar equipment. It is also worth mentioning that further improvements in the results could be achieved by analyzing additional planning scenarios. Therefore, it is crucial for the decision-maker to carefully evaluate multiple planning scenarios before making a final decision.

In this regard, both methodologies proved to be efficient in generating integrated infrastructure allocation plans within a reasonable execution time, allowing for the analysis of multiple scenarios. The execution time for each scenario was approximately 30 min, demonstrating the feasibility of using these methodologies for planning purposes. Furthermore, the versatility of these methodologies is evident in their application to areas of different sizes. This was demonstrated through the successful application of the methodologies to three instances with varying areas of 160 ha, 328 ha, and 580.54 ha, respectively.

Finally, a comparison between the two strategies (Table 17) revealed that, overall, strategy B outperformed strategy A. In the majority of the nine evaluated scenarios, strategy B resulted in lower densities of roads

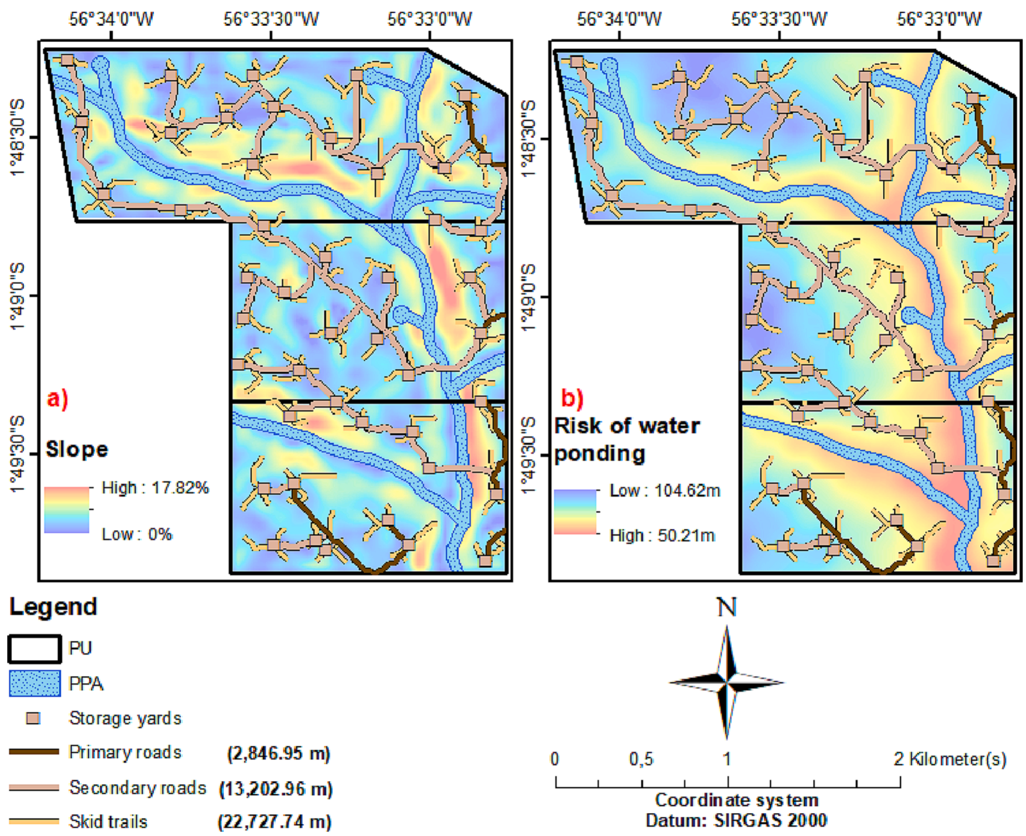


Fig. 12. Deviations from the best solution obtained in strategy B considering ecological and spatial restrictions for Instance 3 and the first scenario. The image allows for observing the deviations applied to the slope of the terrain (a) and areas susceptible to water ponding (b).

and trails. On average, the solutions obtained by strategy B had a density of roads and trails that was 2% lower than those of strategy A. In terms of deforested land, strategy B achieved solutions with, on average, 3.6% less deforested land compared to strategy A. In terms of cost, strategy B achieved solutions that were, on average, 5.6% lower in cost compared to those of strategy A.

However, it is important to consider the inherent advantages and disadvantages of each strategy. Strategy B, for instance, offers more flexibility as it does not require predetermined starting and ending points for primary roads, allowing the method to determine when a road will be primary or secondary. On the other hand, strategy A resulted in a greater extension of primary roads, which facilitates the flow of wood. Another crucial aspect is the ability of both strategies to generate optimized infrastructure allocation layouts, enabling decision-makers to explore numerous scenarios, analyze quantitative results, conduct a qualitative assessment of the layout, and make specific refinements when necessary in the decision-making process.

5. Conclusion

The results demonstrate that the location of storage yards has a direct influence on optimizing the arrangement of roads and skid trails. Thus, we have concluded that it is important for the decision-maker, responsible for infrastructure planning, to evaluate scenarios that combine different quantities of yards to support their decision-making process and determine the final layout of the planning.

In general, strategy B yielded better average quantitative results in terms of cost reduction (approximately 6.5%) and deforested land (approximately 4%). Scenario 2, which involved a reduction in the number of storage yards, consistently resulted in lower costs, around 36% in strategy A and 42% in strategy B, as well as reduced deforested land for both strategies, averaging 11% for strategy A and 18% for strategy B.

In both strategies, a lower number of storage yards resulted in lower infrastructure costs and a smaller area of deforested land. However, it is important to consider that reducing the number of storage yards led to an increase in skidding trails (with an average increase of 26% for both strategies), and the dragging activity can cause more damage to the remaining forest.

CRediT authorship contribution statement

Marcelo Otone Aguiar: Conceptualization, Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis. **Gilson Fernandes da Silva:** Supervision, Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis, Project administration. **Geraldo Regis Mauri:** Conceptualization, Methodology, Investigation, Formal analysis, Software, Supervision, Writing – review & editing, Validation, Visualization. **Adriano Ribeiro de Mendonça:** Conceptualization, Data curation, Formal analysis, Writing – review & editing, Validation, Visualization. **Evandro Ferreira da Silva:** Conceptualization, Methodology, Investigation, Formal analysis, Project administration, Supervision, Writing – review & editing, Visualization. **Evandro Orfano Figueiredo:** Conceptualization, Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis. **Jeferson Pereira Martins Silva:** Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis. **Valéria Alves da Silva:** Conceptualization, Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis. **Rodrigo Freitas Silva:** Conceptualization, Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis. **Gabriel Lessa Lavagnoli:** Formal analysis, Writing – review & editing, Writing – original draft, Formal analysis.

Table 16
Computational results for roads and trails of strategy B.

Instance	Scenario	Yards objective function	Infrastructure	Length (m)	Density (m.ha^{-1})	Avg density (m.ha^{-1})	Objective function (m)
1 (160 ha)	1	105,462.86	Primary	2,753.67	17.21	12.42	3,827.37
			Secondary	1,101.95	6.89	13.22	1,111.95
			Skid trails	4,973.31	31.08	33.40	5,313.09
			Total	8,828.93	55.18	Time Sol (s)	37.81
	2	154,697.90	Primary	992.06	6.20	6.20	1,871.74
			Secondary	1,504.29	9.40	9.40	2,077.05
			Skid trails	6,241.54	39.01	40.13	6,577.91
			Total	8,737.89	54.61	Time Sol (s)	79.28
	3	88,264.51	Primary	1,306.87	8.17	10.70	1,423.52
			Secondary	3,601.82	22.51	21.42	4,465.92
			Skid trails	3,681.65	23.01	23.23	4,019.48
			Total	8,590.34	53.69	Time Sol (s)	28.05
2 (328 ha)	1	258,749.39	Primary	1,454.83	4.44	6.61	1,573.35
			Secondary	7,008.16	21.37	19.74	8,275.29
			Skid trails	13,361.15	40.74	40.73	14,473.55
			Total	21,824.14	66.55	Time Sol (s)	131.28
	2	360,000.71	Primary	1,432.13	4.37	4.88	1,629.00
			Secondary	3,969.82	12.10	12.97	4,957.14
			Skid trails	15,042.02	45.86	46.27	16,069.11
			Total	20,443.97	62.33	Time Sol (s)	239.54
	3	217,892.37	Primary	1,880.41	5.73	6.13	2,087.62
			Secondary	8,296.42	25.29	25.96	10,253.27
			Skid trails	10,245.78	31.24	32.39	11,326.73
			Total	20,422.61	62.26	Time Sol (s)	95.21
3 (580.54 ha)	1	471,092.80	Primary	2,846.95	4.90	4.06	3,041.99
			Secondary	13,202.96	22.74	23.84	15,772.62
			Skid trails	22,727.74	39.15	39.55	24,723.05
			Total	38,777.65	66.79	Time Sol (s)	307.17
	2	731,188.39	Primary	2,948.76	5.08	3.83	3,388.43
			Secondary	6,921.67	11.92	14.82	8,339.30
			Skid trails	28,090.75	48.39	48.48	29,544.23
			Total	37,961.18	65.39	Time Sol (s)	598.93
	3	469,928.31	Primary	2,284.47	3.94	3.13	3,386.97
			Secondary	16,180.88	27.87	31.05	18,554.63
			Skid trails	18,570.96	31.99	31.86	20,353.69
			Total	37,036.31	63.80	Time Sol (s)	262.67

Table 17
Comparison of proposed plans.

Instance	Scenario	Planning	Length (m)	Density (m.ha^{-1})	Deforested land (ha)	Cost (BRL)
1	1	Strategy A	9,063.76	56.65	6.00	11,287.42
		Strategy B	8,828.93	55.18	6.35	12,286.20
	2	Strategy A	9,318.14	58.24	5.59	8,056.39
		Strategy B	8,737.89	54.61	5.05	6,902.67
	3	Strategy A	8,611.55	53.82	6.28	14,265.84
		Strategy B	8,590.34	53.69	6.17	13,910.53
2	1	Strategy A	21,565.50	65.75	13.39	21,999.57
		Strategy B	21,824.14	66.54	12.92	20,635.26
	2	Strategy A	21,270.87	64.85	12.38	16,432.36
		Strategy B	20,443.97	62.33	11.23	13,724.66
	3	Strategy A	20,700.88	63.11	13.94	27,813.84
		Strategy B	20,422.62	62.26	13.32	26,285.16
3	1	Strategy A	39,251.24	67.61	23.86	39,431.71
		Strategy B	38,777.64	66.80	23.30	38,406.94
	2	Strategy A	38,658.42	66.59	21.62	26,898.69
		Strategy B	37,961.18	65.39	20.89	25,282.98
	3	Strategy A	37,572.16	64.72	24.79	49,826.60
		Strategy B	37,036.32	63.80	23.80	47,073.69

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was partly supported by the National Council for Scientific and Technological Development – CNPq (Process 303850/2022-1), Foundation for the Support of Research and Innovation of Espírito Santo - FAPES (Process 2021-F8GXG) and Coordination for the Improvement of Higher Education Personnel (CAPES). This support is gratefully acknowledged. The authors thank the reviewers for their valuable suggestions.

References

Aguiar, M.O., Silva, G.F., Mauri, G.R., Silva, E.F., Mendonça, A.R., Silva, J.P.M., Silva, R. F., Santos, J.S., Lavagnoli, G.L., Figueiredo, E.O., 2020. Metaheuristics applied for storage yards allocation in an Amazonian sustainable forest management area. J. Environ. Manage. 271, 110926 https://doi.org/10.1016/j.jenvman.2020.110926.

Aguiar, M.O., Silva, G.F., Mauri, G.R., Mendonça, A.R., Santana, C.O., Marcatti, G.E., Silva, M.L., Silva, E.F., Figueiredo, E.O., Silva, J.P.M., Silva, R.F., Santos, J.S., Lavagnoli, G.L., Leite, C.C.C., 2021. Optimizing forest road planning in a sustainable forest management area in the Brazilian Amazon. J. Environ. Manage. 288, 112332 https://doi.org/10.1016/j.jenvman.2021.112332.

Akay, A.E., 2006. Minimizing total costs of forest roads with computer-aided design model. Sadhana 31, 621–633. https://doi.org/10.1007/BF02715918.

Amaral, P., Veríssimo, A., Barreto, P., Vidal, E., 1998. Floresta para sempre: um manual para a produção de madeira na Amazônia.

Arima, E.Y., Walker, R.T., Sales, M., Souza Jr., C., Perz, S.G., 2008. The fragmentation of space in the Amazon Basin. Photogramm. Eng. Remote Sens. 74, 699–709. https://doi.org/10.14358/PERS.74.6.699.

Braz, E.M., Passos, C.A.M., Oliveira, L.C., Oliveira, M.V.N., 2005. Manejo e exploração sustentável de florestas naturais tropicais: opções, restrições e alternativas. Embrapa Florestas-Documentos (INFOTECA-E) 10, 42.

Contreras, M., Chung, W., 2007. A computer approach to finding an optimal log landing location and analyzing influencing factors for ground-based timber harvesting. Can. J. For. Res. 37, 276–292. https://doi.org/10.1139/x06-219.

Epstein, R., Weintraub, A., Sapunar, P., Nieto, E., Sessions, J.B., Sessions, J., Bustamante, F., Musante, H., 2006. A combinatorial heuristic approach for solving real-size machinery location and road design problems in forestry planning. Oper. Res. 54, 1017–1027. https://doi.org/10.1287/opre.1060.0331.

Ezzati, S., Najafi, A., Yaghini, M., Hashemi, A.A., Bettinger, P., 2015. An optimization model to solve skidding problem in steep slope terrain. J. For. Econ. 21, 250–268. https://doi.org/10.1016/j.jfe.2015.10.001.

FFT, F.F.T., 2002. manual de procedimentos técnicos para condução de manejo florestal e exploração de impacto reduzido.

Figueiredo, E.O., Braz, E.M., D'oliveira, M.V.N., 2007. Manejo de precisão em florestas tropicais: modelo digital de exploração florestal. Embrapa Acre, Rio Branco, AC.

Graetz, D.H., Sessions, J., Garman, S.L., 2007. Using stand-level optimization to reduce crown fire hazard. Landsc. Urban Plan. 80, 312–319. https://doi.org/10.1016/j.landurbplan.2006.10.011.

Holmes, T.P., Blate, G.M., Zweede, J.C., Pereira, R., Barreto, P., Boltz, F., Bauch, R., 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. For. Ecol. Manage. 163 (1-3), 93–110. https://doi.org/10.1016/S0378-1127(01)00530-8.

Kirkpatrick, S., Gelatt, C.D., Vecchi, M.P., 1983. Optimization by simulated annealing. Science 220 (4598), 671–680.

Pape, U., 1974. Implementation and efficiency of Moore-algorithms for the shortest route problem. Math. Program. 7, 212–222. https://doi.org/10.1007/BF01585517.

Philippart, J., Sun, M., Doucet, J.-L., Lejeune, P., 2012. Mathematical formulation and exact solution for landing location problem in tropical forest selective logging, a case study in Southeast Cameroon. J. For. Econ. 18, 113–122. https://doi.org/10.1016/j.jfe.2011.11.002.

Picard, N., Gazull, L., Freycon, V., 2006. Finding optimal routes for harvesting tree access. Int. J. For. Eng. 17, 35–50. https://doi.org/10.1080/14942119.2006.10702534.

Pinard, M.A., Putz, F.E., Tay, J., Sullivan, T.E., 1995. Creating timber harvest guidelines for a reduced-impact logging project in Malaysia. J. For. 93, 41–45.

Sessions, J., Boston, K., Wing, M.G., Akay, A.E., Theisen, P., Heinrich, R., 2007. Forest road operations in the tropics. Springer International Publishing, New York, NY, USA.

Silva, E.F., 2019. Planejamento da exploração em florestas nativas manejadas da amazônia por meio de pesquisa operacional. Universidade Federal Do Espírito Santo.

Silva, E.F., Silva, G.F., Figueiredo, E.O., Binoti, D.H.B., Mendonça, A.R., Torres, C.M.M. E., Pezzopane, J.E.M., 2018. Allocation of storage yards in management plans in the amazon by means of mathematical programming. Forests 9, 127. https://doi.org/10.3390/f9030127.

Silva, E.F., Silva, G.F., Figueiredo, E.O., Mendonça, A.R., Santana, C.O., Fiedler, N.C., Silva, J.P.M., Aguiar, M.O., Santos, J.S., 2020. Optimized forest planning: allocation of log storage yards in the Amazonian sustainable forest management area. For. Ecol. Manage. 472, 118231 https://doi.org/10.1016/j.foreco.2020.118231.

Sist, P., 2000. Reduced-impact logging in the tropics: objectives, principles and impacts. Int. For. Rev. 3–10.

Søvde, N.E., Løkketangen, A., Talbot, B., 2013. Applicability of the GRASP metaheuristic method in designing machine trail layout. Forest Sci. Technol. 9, 187–194. https://doi.org/10.1080/21580103.2013.839279.

Sterenczak, K., Moskalik, T., 2015. Use of LIDAR-based digital terrain model and single tree segmentation data for optimal forest skid trail network. iForest - Biogeosciences For. 8, 661–667. https://doi.org/10.3832/ifor1355-007.

Walker, R., Arima, E., Messina, J., Soares-Filho, B., Perz, S., Vergara, D., Sales, M., Pereira, R., Castro, W., 2013. Modeling spatial decisions with graph theory: logging roads and forest fragmentation in the Brazilian Amazon. Ecol. Appl. 23, 239–254. https://doi.org/10.1890/11-1800.1.