Floresta e Ambiente 2019; 26(1): e20170543
https://doi.org/10.1590/2179-8087.054317
ISSN 2179-8087 (online)

Original Article

Forest Management

Development of Mathematical Programming Model for Cable Logging System Location

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ABSTRACT

Defining the optimum points for installing of a cable logging system is a problem faced by forestry planners. This study evaluated the application of a mathematical programming model for optimal location of cable logging in wood extraction. The study was conducted in a forestry company located in Parana State, Brazil. We collected data during timber harvesting and developed mathematical models to define the optimal location of the cable logging considering the variables "cycle time" and "extraction distance". The variable "cycle time" affected the definition of the optimal location of equipment resulted in a reduced number of installation points with the largest coverage area. The variable "distance extraction" negatively influenced the location, with an increased number of installation points with smaller coverage. The developed model was efficient, but needs to be improved in order to ensure greater accuracy in wood extraction over long distances.

Keywords: forest extraction, productivity, planning, optimization.

1. INTRODUCTION

Wood logging in mountainous regions has always represented a challenge for Brazilian forestry companies, requiring efficient planning of the operations and the use of specific equipment in these conditions, as productivity under these conditions is low and operating costs are high.

The use of cable logging system is a technically feasible alternative for wood extraction under these operating conditions, especially when road access is limited and greater care is required to protect the terrain. Lopes et al. (2011) also mention that the cable logging system allows the removal of wood from difficult-to-access areas with low environmental impact.

Therefore, due to the complexity of the operation, planning wood harvest with cable logging has become of fundamental for optimizing operations and to reduce production costs (Lopes et al., 2003). This is a complex and challenging task for forest managers, and the system physical viability, economic efficiency and environmental issues should be considered (Stampfer et al., 2006). Ghaffariyan et al. (2009) state that some important aspects need to be considered in planning operations with cable logging system, such as topographic conditions, volume of wood to be extracted, distance and width of the extraction range, cutting method, capacity and installation location of the equipment, among others. Chung et al. (2004) mentions that the planning should also identify the location of the wood deposit and the access road conditions.

However, contrary to what happens in other countries, planning of wood harvest using aerial cable in Brazil has been empirically executed, without detailed information. It demands high execution time, low productivity and high operating costs. Most forest companies have only used topographic maps and basic functions of the geographic information system (GIS) to assist in decision making for their operational planning; however, these are slow processes that do not allow for evaluating a set of variables, impairing the right decisions (Epstein et al., 2006).

Meanwhile, other countries use computerized methods that can assist in planning operations with cable logging (Epstein et al., 2006; Chung et al., 2004), such as: LoggerPC, which is a program for analyzing the load capacity of aerial cable systems; PLANS (*Preliminary Logging Analysis System*), which allows for analyzing wood harvesting units and the location of unloading yards from topographic information on the terrain; CPLAN, which is a method that incorporates software languages, a geographic information system and heuristic techniques to optimize the wood extraction, defining the optimal extraction route and the location of the wood stockyards and roads; and finally PLANEX, which combines heuristic solutions and mixed integer programming to optimize the operations, contemplating the optimum location of the equipment.

It is also important to highlight that the computer-assisted planning of operations with cable logging system will allow the planner to obtain new ways of approaching operational problems, increasing perspectives in the search for better solutions with a greater number of operational variables. Moreover, computerized methods allow for creating and evaluating several alternatives simultaneously, enabling managers to solve complex problems in a short period of time.

Therefore, this study aimed to evaluate the application of a mathematical programming model for the optimal location of a cable logging system for wood extraction in mountainous regions, seeking to aid in operations planning, to increase productivity and minimize operational costs.

2. MATERIAL AND METHODS

2.1. Characterization of the study area

The study was carried out in the operational area of a forest company located in the Vale do Ribeira, Tunas do Parana, State of Parana, Brazil, between parallels 24°58’28”S and 49°05’09”W, with an average altitude of 906 meters.

The region’s climate according to the KÖPPEN classification is humid temperate (Cfa), characterized by infrequent frost, rainfall distributed throughout the year and an average annual temperature of 18 °C. The region’s relief ranges from undulated to strongly-undulated, with large altimetric gradients (EMBRAPA, 1999).

Data were collected in *Pinus taeda* stands in an experimental area of 23.5 hectares, and the characteristics are shown in Table 1.

The company used a full tree wood harvesting system, in which tree felling is carried out by a team of

Table 1. Characteristics of the forest stands.

Item	Value
Variation of slope of the studied area (degrees)	0 to 45
Age of the stand (years)	27
Density of the stand (tree/ha)	1.358
Basal area of the stand (m^2/ha)	56.62
Mean diameter of the trees (DBH) (cm)	23.1
Average height of the trees (m)	22.3
Average individual tree volume (m^3/tree)	0.41
Average volume of the stand (m^3 / ha)	556.7
Spacing (m)	3 x 2.45

chainsaw operators. This is followed by tree extraction from the interior to the roadside, and the subsequent processing of the wood by an aerial cable system, consisting of a tower mounted on a truck equipped with a *Konrad* Mounty 4000 processor head. The tower height is of 13.1 m, length of the master cable and traction of 550 m and 650 m, respectively, equipped with four anchor cables.

2.2. Preparation of the study area imaging

Land use maps, contours and TINs (*Triangulated Irregular Network*) of the study area were initially obtained from stereoscopic images of the WorldView-2 satellite. We used a DGPS receiver to obtain sixteen (16) planialtimetric control points in order to perform orthorectification of the image, and to generate the topographic map with 10-meter equidistant level curves. The digital terrain model was developed for the altimetric variable, and the elevation map was later obtained by slicing the altimetric model. The altimetric model was converted to slope in degrees and then sliced into six slope classes: 0 to 7°; 8 to 14°; 15 to 20°; 21 to 30°; 31 to 44° and over 45°.

2.3. Data collection

2.3.1. Determination of time and productivity extraction

We carried out a study of the time and movement of wood extraction using the cable logging to obtain the average time of the operational cycle, productivity at different extraction distances and terrain slopes. The data were then later used in the proposed planning models.

Productivity of the cable logging was obtained by the average volume of trees provided by the company inventory, this value was multiplied by the number of extracted trees in the operating cycles by the equipment, and divided by the hours actually worked. Equipment productivity was obtained for the following slope classes: 0 to 7°; 8 to 14°; 15 to 20°; 21 to 30°; 31 to 44° and over 45°; and at the extraction distances of: 0 to 200, 201 to 400, 401 to 600, 601 to 800 and over 801 m.

2.3.2. Defining the aerial cable system location points

Using ArcGIS software, a mesh of 10 × 10 m points was superimposed over the study area, defining each mesh point as a cell unit to determine the attributes for the mean volume of wood (m^3), distance between cells, and the potential location points of the equipment through the digital terrain model (DTM). The attributes of time spent and productivity for removing the wood in each cell were estimated. The data was then grouped in a database to later construct the models and to perform simulations for the optimal location of the aerial cable system.

Next, 136 potential location points of the cable logging were demarcated in the road network of the study area using a GPS receiver (Figure 1), taking into account the following operational restrictions: anchor cable positioning; master cable length; relief/terrain characteristics; tower height; number of support trees; number of cells covered by the system in the different location points; operational cycle time; average and maximum extraction distance, volume of wood to be extracted per operating cycle; slope classes; terrain elevation; presence of roads; maximum width of the extraction area for wood removal (50 meters); and the equipment productivity.

2.4. Problem formulation

The Integer Linear Programming (ILP) technique was used to define the optimal points for installing the cable logging system in the study area, whose main function was to minimize the operational cycle time and the extraction distance.

Operational cycle time, distance, declivity/slope and volume of wood values were determined for each binary variable X_{ij}, which assumes value 1 if the cell i volume is extracted to the tower in the j position, and

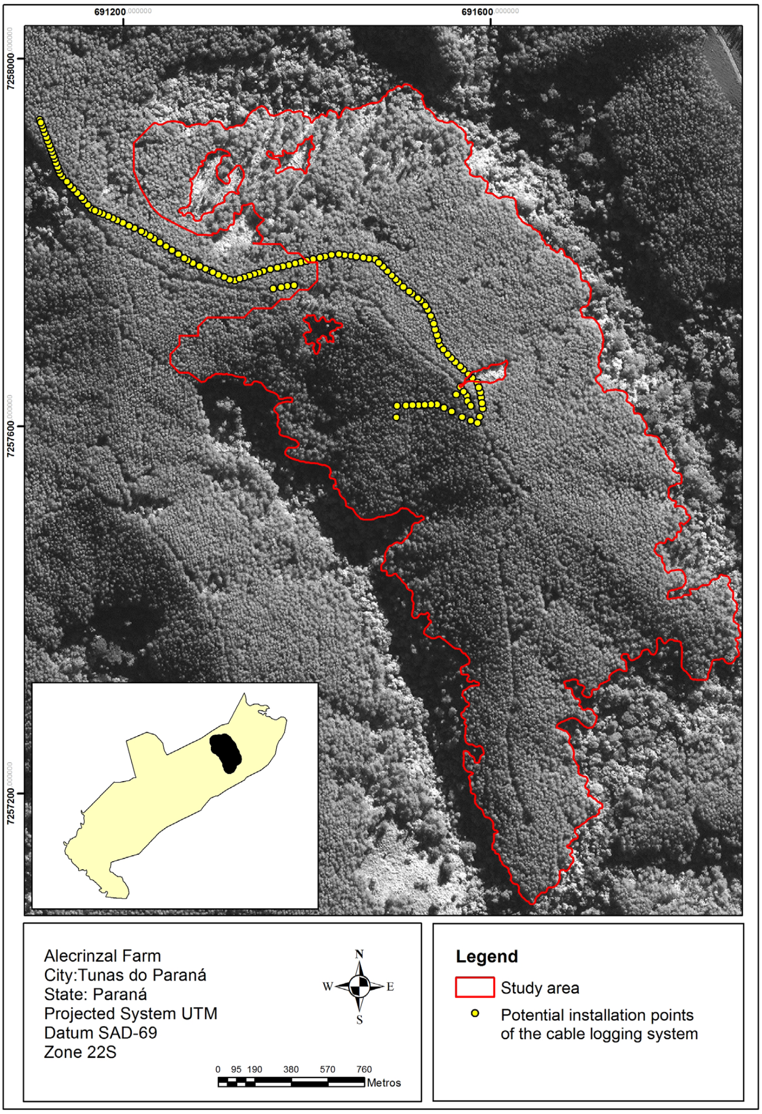

Figure 1. Map image representing the potential installation points of the cable logging system on a stretch of road in the study area.

as 0 otherwise. The DP_{ij} distance was calculated by the slope *sine*; if the result was negative, it was disregarded and assumed an arbitrary value of 999 m in order to avoid dragging the wood in the direction of the slope.

DP_{ij} = Distance weighted by the slope *sine*.

If the slope is negative, $DP_{ij} = 999$

An arbitrary penalty of 10,000 was applied for each installation point of the aerial cable system, representing a symbolic cost, avoiding the selection of an excessive number of points and the possibility of using all available installation points in attending the previously defined restrictions and penalties. Thus, the model was limited to selecting the best installation points according to the objective function and their respective operational restrictions.

The variables considered in the model were:

$X_{ij} = 1$, if cell i is extracted to the tower j;

0, otherwise

$T_j = 1$, if the tower j is active;

0, otherwise

The following objective function was used to minimize the extraction distance of the wood with the aerial cable logging system and the subsequent movement of the equipment as a function of slope (Equation 1):

$$\text{Min } Z = \sum_i \sum_j (DPij * Xij) + 10.000 * \sum_j (Tj) \quad (1)$$

in which: i = cells with wood to be extracted; j = potential tower positions; DP_{ij} = distance weighted by the slope *sine* between the i cell and the j tower position.

If the slope was negative, $DP_{ij} = 999$;

$X_{ij} = 1$, if the wood from cell i is extracted by the tower j; 0, otherwise;

$T_j = 1$, if the potential position of the tower j is used; 0, otherwise.

The respective objective function was used to minimize the operational cycle time of the wood extraction as a function of slope and extraction distance (Equation 2):

$$\text{Min } Z = \sum_i \sum_j (Tij * Xij) + 10.000 * \sum_j (Tj) \quad (2)$$

$X_{ij} = 1$, if cell i is extracted to the tower j;

0, otherwise

$T_j = 1$, if the tower j is active;

0, otherwise

in which: i = cells with wood to be extracted; j = potential tower positions; T_{ij} = time required for the wood from cell i to be taken up to tower j;

$X_{ij} = 1$, if the wood from cell i is extracted by the tower j; 0, otherwise;

$T_j = 1$, if the potential position of the tower j is used; 0, otherwise.

The constraints used in the optimization model were:

1. Each cell i sends wood to a single tower j.

$$\sum_j Xij = 1$$

$i = 1, 2, \ldots n$

2. T_j is a binary variable that can be either 0 or 1. Therefore, it is a constraint that causes no volume to be collected if tower T_j is disabled ($T_j = 0$), and that allows up to 10,000 m^3 to be harvested if tower T_j is activated ($T_j = 1$).

$$\sum_i Xij \le 10.000\ Tj$$

$j = 1, 2, \ldots T$

The developed models were then applied to the study area, comparing both scenarios, and containing 136 possible points for the aerial cable logging system location. The geographical coordinates of the potential location points, the information concerning the cells that composed the mesh of points, as well as the geographic coordinates, volume of wood, relief and wood extraction data were tabulated into an Excel spreadsheet and analyzed using LINGO software.

2.5. Statistical analysis

The model was defined based on regression equations, considering the adjusted coefficient of determination (R^2aj), the standard error of the absolute and percentage estimate (S_{yx} and S_{yx} %), the F value and graphical waste analysis as a percentage. The models that presented the best adjustments were applied in a productivity variation estimation of the aerial cable system and the operational cycle time in the different classes of extraction distance.

The results obtained from the mathematical models were then spatialized and analyzed using ArcGIS software in order to select the best scenario for the aerial cable logging system location, considering optimized wood logging planning.

3. RESULTS AND DISCUSSION

3.1. Optimum installation in the scenario of minimizing the operational cycle time

Figure 2 shows 6 of the 29 possible locations for the cable logging system (green dots) selected by the model, with the respective coverage area (red areas) in the scenario of minimizing operational cycle time. In this scenario, the model pointed to a reduced number of installation points, resulting in areas with higher coverage and higher volume of wood, thus contributing to lesser equipment movement in the harvesting area.

However, the model was not able to spatialize the extraction area in narrow bands along the study area; a similar situation to what occurs in the field. This situation can be attributed to the relief's and marked slope, as well as to the restrictions imposed

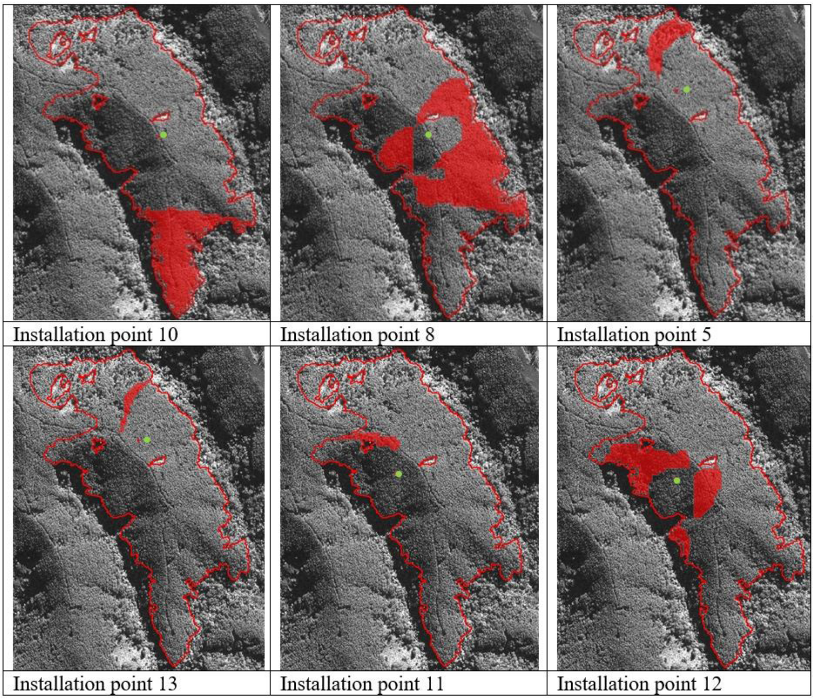

Figure 2. Optimum installation simulation of the cable logging system (green points) in the scenario to minimize the operational cycle time of extraction and their coverage areas (red areas).

so that the equipment covered a larger area, avoiding excessive movement in the study area.

Chung et al. (2004) carried out studies aiming at the optimal installation of a cable logging system by assuming the places occupied by the equipment, incorporating a computerized model into the method. Although the solution showed limitations, the algorithm application was able to provide a useful preliminary arrangement for the aerial cable system location.

We also observed larger extraction sites covering larger areas and with wider bands, which can lead to a greater lateral displacement distance of the drag cable; meaning, bands with widths greater than 50 m. In practical terms, such situation could compromise the equipment's operational efficiency and productivity due to the high dragging distance of the trees up to the equipment's master cable.

Another important aspect to be observed in this scenario refers to the fact that wood harvesting areas are not sequentially located and immediately after the start of the extraction area, preventing the equipment's coverage and the extraction of wood from the installation starting point. This result can be explained by the high extraction distance contemplated by the model in solving problem, which pointed out areas with greater coverage.

Table 2 presents the partial results for the scenario of minimizing operational cycle time of extraction at each equipment installation point. As can be seen, installation points with lower slope and extraction distance contributed to higher equipment productivity.

When comparing the installation points 5, 8 and 10, a decrease in the extraction distance and slope of the terrain is verified. This resulted in increased productivity, but with a reduction in the equipment coverage area. When comparing the installation points 5 and 12, we noticed that the second one presented smaller extraction and slope distance, again with an increase in the equipment's coverage area and productivity of 2.18 ha and 1.3 m^3 h^{-1} higher, respectively.

On the other hand, the installation points 8 and 10 presented a larger coverage area, and consequently a greater average extraction distance. Considering that these areas have a greater average slope, the equipment productivity was lower in relation to the other equipment installation points.

Table 2. Partial results for the scenario of minimizing cycle time.

Location point	Extraction time (h)	Average extraction distance (m)	Volume Extracted/Point (m^3)	Area (ha)	Average Slope (degrees)	Productivity (m^3 h^{-1})
5	8.92	153.59	723.71	1.30	12.60	18.92
8	64.60	171.09	4.436.90	7.97	18.64	17.80
10	49.02	361.25	2.271.34	4.08	18.83	14.29
11	2.05	119.51	345.15	0.62	6.81	22.12
12	18.87	117.40	1.937.32	3.48	7.86	20.22
13	3.35	117.00	322.89	0.58	10.31	19.90
Sum	146.80	-	10.037.30	18.03	-	-
Mean	24.47	173.31	1.672.88	3.01	12.51	18.88

Finally, we observed that the mean slope in the study area presented low values caused by the relief characteristics, where normally the stand entrances had steep slopes with variations in the interior. In most cases, this situation made it difficult to access the machines for extracting wood, thus justifying the use of cable logging system.

3.2. Optimal location in the scenario of minimizing extraction distance

In the scenario of minimizing the extraction distance, we observed a greater number of points selected for the cable logging system installation, represented by 94 points. This situation can be explained by the model's objective, which sought an optimal solution of the cells being closest to each installation point, thus contributing to a reduction in the extraction distance.

Therefore, when installed at a smaller extraction distance (up to 200 m), the equipment may, even with the increase in productivity within the operating cycles, lead to a reduction in the final production, as there will be a need to constantly move the master cable and to assemble/reassemble the equipment along the study area. This situation will imply in lower stand extraction production and increase extraction costs.

Figure 3 shows 6 of the 94 possible optimal installation positions for the cable logging (green dots) as selected by the model with their respective coverage area (red areas). In each interaction, the model installed the equipment in a viable location according to the criterion of the lowest extraction distance. We observed that, similarly to what happens in the field, the proposed model was able to separate the areas into narrow extraction bands within most of the study area. Installation point 10 suggested by the model was located closer to the other points in the lower part of the studied area, resulting in the larger coverage area for the wood extraction.

It is essential to emphasize the importance of the generation of narrow wood extraction areas, allowing better allocation of the equipment due to the limitation imposed by the guillotine cable length, which makes it impossible to extract at a lateral distance greater than 25 m on either side of the master cable. In this scenario, the wood harvesting areas indicated by the model were located immediately after the beginning of the extraction range. This occurred considering that the model sought for the cells to be located near the equipment installation points as the optimal solution, justifying the greatest number of selected location points; which led to the existence of no areas without the possibility of performing the wood extraction between the equipment installation point and the extraction area, thus avoiding displacement of the self-propelled conveyor in areas where there is no wood to be extracted.

Finally, it is noteworthy that the model in this scenario did not result in an optimized division of the extraction ranges, which can be executed in the field when the extraction distance exceeds 200 m. Therefore, the ideal shape of the extraction ranges in these relief conditions should be triangular, with a broad base of up to 50 m wide and with a narrow apex/top.

Chung et al. (2004) said that the results of the computerized models should be considered as "pre-planning" to support the aerial cable system

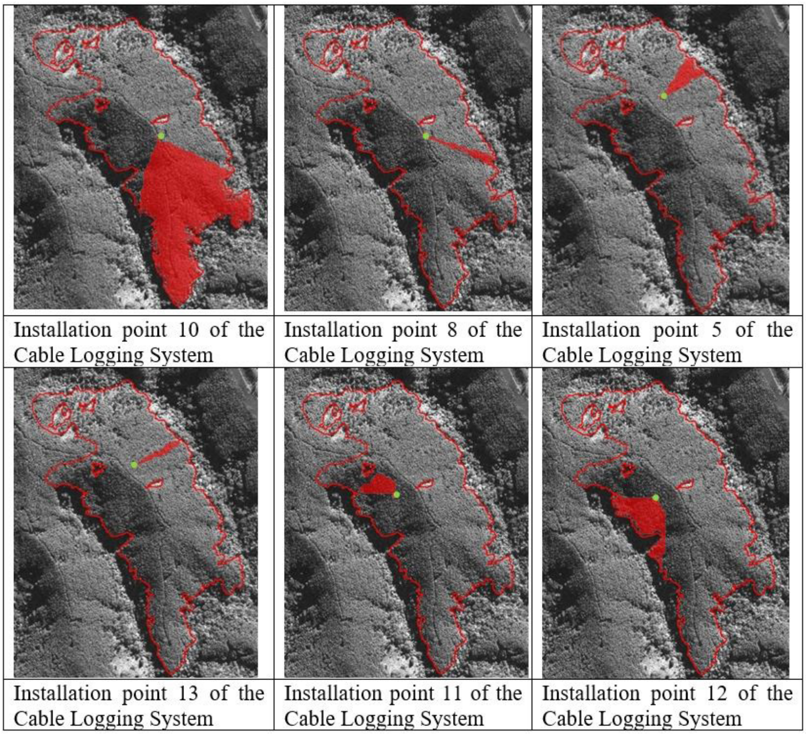

Figure 3. Simulation of the optimal cable logging system installation in the scenario for minimizing distance extraction and their respective coverage area (red areas).

operations. As the solutions are determined exclusively by technical and cost feasibility, the model's best solutions do not always represent the best alternatives from the practical point of view.

Table 3 presents the partial results for the scenario of minimizing the extraction distance at each cable logging installation point. As observed, installation point 11 presented a lower average extraction distance, accompanied by a lower slope and consequently higher productivity; while point 10 presented lower productivity affected by the greater coverage area and average extraction distance, thus ratifying the influence of these variables on the cable logging system's productivity.

When comparing the partial results, we notice that installation points 5, 8, 10, 11, 12 and 13 were selected in both scenarios as the best location points for the wood extraction equipment. This shows the feasibility of using simulators as a tool to support wood harvesting with cable logging. It is also possible to notice that in this scenario the installation points presented a larger coverage area, however with a lower mean slope for all cases when compared to the scenario of minimizing the extraction distance. Moreover, the model penalized the coverage area, determining that the equipment was allocated with a larger coverage area, thus reducing unproductive times caused by changes in equipment for assembly and disassembly. The model also penalized the slope, defining the extraction ranges in places of greater slope so that the objective of reducing the extraction distance was reached.

Finally, it should be noted that the equipment productivity in both scenarios was similar. However, according to the objective of each scenario, the model penalized the variables in different ways in order to achieve the proposed objectives. Thus, the potential of the computational model proposed as a support tool in planning wood harvesting using cable logging became evident, allowing the planner to estimate operating cycle times and extraction distance, to set the best layout for equipment location in advance with greater coverage area and reduced movement between installation points.

Table 3. Partial results for the scenario of minimizing the extraction distance.

Location point	Extraction time (h)	Average extraction distance (m)	Volume Extracted/Point (m^3)	Area (ha)	Average slope (degrees)	Productivity (m^3 h^{-1})
5	5.28	100.54	384.12	0.69	25.45	18.19
8	5.28	152.61	356.29	0.64	22.29	17.66
10	90.52	270.02	4.876.69	8.76	20.06	15.80
11	2.72	62.36	361.86	0.65	7.18	21.31
12	13.77	95.28	1.013.19	1.82	25.46	18.29
13	2.92	93.83	211.55	0.38	26.55	18.17
Sum	120.48		7.203.70	12.94		
Mean	20.08	129.11	1.200.62	2.16	21.17	18.24

4. CONCLUSIONS

- The operational cycle extraction time affected the cable logging system, resulting in fewer installation points with larger extraction coverage areas;
- The variable extraction distance affected the cable logging installation, resulting in a greater number of installation sites, minimizing the extraction distance and the equipment's movement;
- The proposed computational model is a promising support tool for planning wood harvesting in mountainous regions, allowing for optimization of the cable logging system's location, despite needing improvements in order to guarantee greater precision in the results.

ACKNOWLEDGEMENTS

The authors acknowled the forestry company by support for this research.

SUBMISSION STATUS

Received: 28 apr., 2017
Accepted: 5 dec., 2017

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FINANCIAL SUPPORT

This work was supported by the CAPES with postgraduate scholarships.

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