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Mathematical formulation and exact solution for landing location problem in tropical forest selective logging, a case study in Southeast Cameroon

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ABSTRACT

In Central Africa, creating forest roads and skid trails is one of the most costly and environmentally damaging operations for the forest's ecosystem. An optimized road network is essential for reducing construction costs and improving the sustainable management of timber resources. The location of landings is vital in the development of a future forest road network. In this study, a binary integer programming model similar to the uncapacitated facility location problem is formulated to optimize the locations of the landings. The model is applied to selective logging in Central Africa and tested on an annual logging zone in Southeast Cameroon. The results are compared to that of manual road planning, the currently used method.

Introduction

Selective logging is the main harvest system in the Congo Basin's forests, where logging intensity varies from 0.5 to 2 trees per hectare under planned logging schemes. For approximately a decade, forest loggers have had to plan logging phases to advance sustainable management of the forest resources (Pinard et al., 1995; Johns et al., 1996; Bertault and Sist, 1997; Durrieu De Madron and Forni, 1998; Sist, 1998). The road planning process which includes the construction of roads, landings and skid trails is

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one of the phases that have major economical and ecological impacts (Sist, 2000). Forest road planning aims to develop an optimal road network that minimizes road density while providing access to the whole logging area in the harvest zone. Every tree felled in a logging area is skidded to a landing. The landings represent both assembly points for skid trails as well as targets for roads that will be opened. A pertinent location of landings can minimize both skidding network and road building cost while reducing forest damages. Because the location of the landings is vital in sustainable selective logging plan, the problem studied in this paper is called the landing location problem (LLP) for easy reference.

Sustainable selective logging in Central Africa is typically carried out as follows. Marketable trees with data such as quality and dimension are first located during logging inventories. After being felled with saw equipment, they must be hauled to landings along the road to be transported by trucks to destinations such as saw mills for further processing. A tree becomes a log when cut. Therefore the terms tree and log are used interchangeably in the text. In order to provide sustainable management and to reduce the impact of their logging, companies are applying different rules. The following rules are common. Most logs are hauled uphill to reduce the impact on soils and to ensure safety. Hauling operations and landing constructions are avoided at a distance shorter than 30 m of streams and sources. Since hauling operations are expensive and destructive, the maximum hauling distance is limited to 1000 m to reduce impact of logging. Logs that are located further away and/or in an inaccessible area may remain uncut. Landing surface is limited to an area of 1000 m^2.

Recent decades have seen a great deal of research focused on forest road planning and optimization (Reutebuch, 1988; Liu and Sessions, 1993; Dean, 1997; Murray, 1998; Epstein et al., 2001; Akay et al., 2004; Anderson and Nelson, 2004). Dean (1997) compared the road planning problem to a multiple target access problem. Freycon and Yandji (1998) developed a computer-aided method to assist forest road planning for selective logging systems in the Congo Basin. Under this method, which describes the steps and spatial analysis tools needed to plan a forest road system, skilled operators have to manually position landing locations based on topography and an inventory of marketable trees. To date, no computerized method for siting landing locations has been tested or applied in the Central African context of selective logging. However, advantageous location of landings is a key factor in minimizing skid trail length and therefore optimizing total forest road network length in order to ensure sustainable management of forest resources.

This paper describes the formulation of a binary integer programming model (BIPM) to optimize landing location for skidding path planning. The model is applied to the LLP in the Central African context of selective logging. The BIPM is solved with CPLEX® that uses branch-and-cut algorithms. The results obtained on an experimental area are discussed and compared with those of manual planning, the currently used method. Future prospects are also outlined.

Formulation of the binary integer programming model

Traditional location problems are separated into two types: problems that attempt to maximize customer satisfaction with a fixed number of facilities and problems that attempt to minimize the number of facilities in order to satisfy all customers (Hammami, 2003). The complexity of the LLP is that the number of facilities (landings) is not known and some customers (trees) may be unsatisfied (uncut or unassigned).

A BIPM is formulated for the LLP to find optimal locations for the landings. A problem with a set of m logs and n candidate landing sites can be represented by a network with $m+n$ nodes and mn arcs. The index set of the m logs is represented by I and the index set of the n candidate landing sites is represented by J. The cost of opening landing j is represented by f_j and the cost of hauling log i to landing j is represented by c_{ij}. Costs are measured in distances, specifically meters, in this application. It is assumed that $f_i > 0$, $\forall j \in J$ and that $c_{ij} \geq 0$, $\forall i \in I$ and $\forall j \in J$. Let C represent the $m \times n$ matrix of the hauling or skidding costs. Let $\hat{c}$ represent the maximum limit on the hauling distance. In this case, $\hat{c} = 1000$. In C, the actual hauling cost c_{ij} is used if $c_{ij} \leq \hat{c}$ and a large number $c_{ij} = \bar{c}$, with $\bar{c} \gg \hat{c}$, is used if $c_{ij} > \hat{c}$ or if a path between i and j is prohibited. A binary variable y_j is used to represent the status of landing j in the model. Landing j will be open only if $y_j = 1$ and will be closed if $y_j = 0$ in the solution. A binary variable x_{ij} is used to represent the status of the skidding path from log i to landing j. Log i will be assigned to landing j only if $x_{ij} = 1$ and will not be assigned to landing j if $x_{ij} = 0$ in the solution. Log i will remain uncut if $x_{ij} = 0\ \forall j \in J$ in the solution. The BIPM for the LLP can be formulated as follows:

$$\min \quad \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{j \in J} f_j y_j + \alpha \left(m - \sum_{i \in I} \sum_{j \in J} x_{ij} \right) \tag{1}$$

$$\text{subject to :} \quad \sum_{j \in J} x_{ij} \le 1 \qquad \forall i \in I \tag{2}$$

$$x_{ij} \le y_j \qquad \forall i \in I, j \in J \tag{3}$$

$$x_{ij} = 0 \quad \text{or} \quad 1 \qquad \forall i \in I, j \in J \tag{4}$$

$$y_j = 0 \quad \text{or} \quad 1 \qquad \forall j \in J \tag{5}$$

A log i cannot be assigned to more than one landing but may remain uncut. This requirement is modeled by the constraints in (2). A log i can be assigned to a landing j only if the landing is open, i.e., $y_j = 1$. This requirement is modeled by the constraints in (3). The constraints in (4) define the values that x_{ij} can take $\forall i \in I$ and $\forall j \in J$ and those in (5) define the values that y_j can take $\forall j \in J$. Because each log i, if ever assigned, is always assigned to the landing such that the hauling cost is the lowest among all open landings, each constraint in (4) can be relaxed to $0 \le x_{ij} \le 1$. In the objective function (1), the first term represents the total hauling cost, the second term represents the total opening cost of the landings and the third term represents penalties of uncut trees where α is a penalty factor applied to the number of unassigned trees. The solution process for the LLP is to decide the landings to open and to decide the assignments of logs to open landings while minimizing the total cost (1).

The LLP model is similar to but different from the standard uncapacitated facility location problem (UFLP). The UFLP model does not have unassigned customers, i.e., the constraint in (2) is of the form $\sum_{j=1}^{n} x_{ij} = 1, \forall i \in I$ (Cornujélos et al., 1990), and consequently does not need to include the penalty term in the objective function (1).

A case study

A case study is described in this section. The case is about the LLP in a tropical forest in Southeast Cameroon. The ArcGis software and the Geodatabase were used to create and manage data about the skidding network, to apply penalty and to visualize results.

Study area and dataset

The study area covered 2562 ha of moist semi-deciduous tropical forest in Southeast Cameroon (3°48′37″E; 3°08′14″N) where the altitude varies between 550 m and 650 m. The logging inventory identified and located 3930 marketable trees, i.e., $m = 3930$.

The digital elevation model was based on Shuttle Radar Topography Mission data generated for the Congo Basin with a 90 m resolution. These data are available from the Global Land Cover Facility (U.S. Geological Survey, 2004). Streams within the area were identified via a digital elevation model using hydrographic spatial analysis tools and field data. A stream layer, derived from the digital elevation model data, was also used to identify streams and riparian areas.

Skidding network design and candidate landing set

The area to be harvested is partitioned into a 20 m × 20 m spaced grid of nodes, called the initial grid, where logs are located, landings can be opened or, otherwise, skidding path intersections can be established. The skidding network is elaborated by creating links between nodes. The digital elevation model was then used to determine the elevations of points and slopes along the skidding network. Undesirable segments were deleted following reduced-impact logging standards in order to avoid

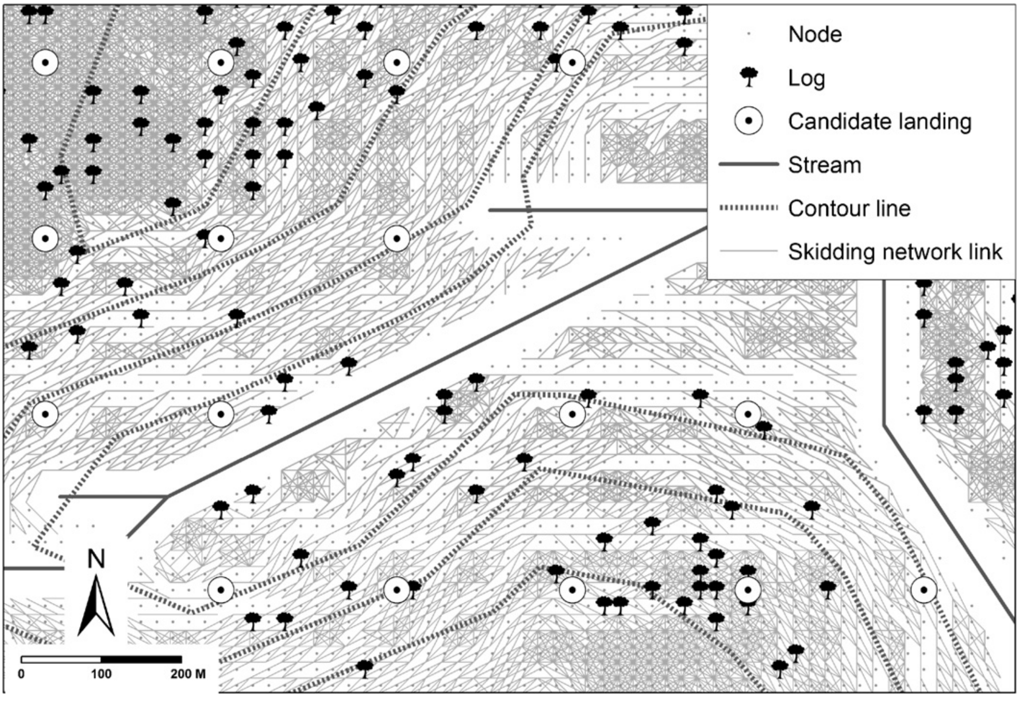

Fig. 1. Study area partitioning.

stream crossing, riparian proximity or steep zones. A deleted path from log i to landing j is reflected in the skidding cost matrix C by setting $c_{ij} = \bar{c}$.

The initial grid is also used as a basis for the candidate landing grids generation. Candidate landing locations are regularly spaced on the initial grid with a defined grid mesh size where the location of the first candidate landing is randomly selected. For example, a candidate landing grid with a grid mesh size of 280 m × 280 m is a sub grid of the initial 20 m × 20 m grid where candidate landings are located at the center of a 14 nodes by 14 nodes square of the initial grid. The area partitioning is represented in Fig. 1.

Landing opening costs and log skidding cost matrix

For each candidate landing j, an initial opening cost of 2500 m is used. In order to promote uphill hauling and higher landing locations, a penalty is assigned to landings located on altitude lower than those of its neighbors. Each candidate landing is associated with a competition zone consisting of a set of competitive candidate landings which are within a distance of 1000 m using the skidding path network. The elevation of each landing is compared to those of the competitive landings and a penalty factor γ is computed. This penalty factor is used in computing the fixed opening cost for the landings. The penalty factor γ varies between 1 and 11. The opening cost f_j of a candidate landing j is obtained by multiplying the initial cost of 2500 m by the penalty factor γ, i.e., $f_j = 2500\gamma$, $\forall j \in J$. Consequently, the opening cost f_j for a candidate landing j may vary between 2500 m (best or cheapest location) and 27,500 m (worst or most expensive location).

The penalty factor γ is computed using (6) in the following

$$\gamma = 1 + \frac{N_h}{N} \times 10 \tag{6}$$

where N_h is the number of competitive landings located on higher elevations in the competition zone and N is the total number of competitive landings in this competition zone. If there are no competitive landings at higher elevations within the competition zone, the penalty factor is fixed to $\gamma = 1$.

As mentioned before, the skidding cost matrix C is used to represent the cost for hauling logs to landings. Unlike in Contreras and Chung (2007), because the differences in elevations of the candidate landings have been factored into the ratio γ, no difference is made between the uphill and downhill skidding costs to avoid double counting. In this study, the cost corresponds to the distance (meters) to reach landings from logs using the skidding path network. The distance c_{ij} from a log i to a landing j is calculated using Dijkstra's shortest path algorithm (Dijkstra, 1959). The large cost $c_{ij} = \bar{c}$ is assigned to a path that is prohibited by the reduced-impact logging standards and stream crossings. In this case study, $\bar{c} = 5000$ is used. As the skidding path network is elaborated considering reduced-impact logging standards and stream crossings by hauling paths, the entire skidding path network is realistic.

Penalty of unassigned trees

Some trees may remain unassigned when they are located in a far away area or when the extra cost needed to extract the log is higher than the potential benefits. They may also be unassigned if the reach zone of a potential landing grid does not cover the entire logging zone (particularly for low density grids or for logging zones with concave boundaries). In this case study, the penalty cost for each unassigned tree is fixed at 5000 m, i.e., $\alpha = 5000$ in the objective function (1).

Results

A computational experiment is conducted using the data in the case study. The BIPM formulated with the data in the case study was solved using the linear, integer and quadratic programming package CPLEX® optimizer via the CPLEX® Optimization Studio 12.2. on a personal workstation with an Intel 3.2 GHz Pentium 4 processor and 3.0 GB of RAM. By varying the grid mesh sizes for the study area and by selecting different first landing location, different test problems are constructed for the case study. The computational experiment consists of two parts with a total of 58 test problems. The first part with 10 test problems was to study the effects of the potential landing grid mesh sizes and the second part with 48 test problems was aimed to assess the sensitivity of the solution on the first potential landing location.

Table 1
Results for different grid mesh sizes.

Grid mesh size (m)	No. of potential landings	No. of landings selected	Total opening cost (m)	Total hauling cost (m)	Total penalty (m)	Total cost (m)	Processing time (s)
700	45	33	443,333	1,441,801	0	1,885,134	5
640	51	38	397,946	1,273,715	15,000	1,686,661	6
580	67	34	326,220	1,353,848	0	1,680,068	8
520	80	38	370,714	1,256,353	0	1,627,067	9
460	103	45	390,297	1,178,994	0	1,569,291	11
400	131	46	336,699	1,188,344	0	1,525,043	15
340	183	52	397,798	1,086,852	0	1,474,650	26
280	294	56	360,755	1,080,217	0	1,440,972	42
220	830			Out of memory			
160	2134			Out of memory			

Table 2
Results for the 48 problems with different first potential landing locations and a 280 m × 280 m grid mesh size.

Solution ID	No. of potential landings	No. of landings selected	Total opening cost (m)	Total hauling cost (m)	Total penalty (m)	Total cost (m)	Processing time (s)
1	294	56	360,755	1,080,217	0	1,440,972	42
2	298	55	363,336	1,061,823	0	1,425,159	43
3	288	56	372,032	1,054,164	0	1,426,196	42
4	291	54	325,017	1,096,238	0	1,421,256	43
5	289	55	345,120	1,079,777	0	1,424,897	50
6	286	55	381,379	1,048,379	0	1,429,759	42
7	300	58	410,162	1,034,619	0	1,444,782	44
8	297	54	376,244	1,072,882	0	1,449,126	53
9	311	56	364,233	1,055,204	0	1,419,437	45
10	299	58	368,624	1,056,434	0	1,425,058	43
11	299	54	343,019	1,083,762	0	1,426,781	56
12	301	58	382,695	1,043,694	0	1,426,388	51
13	297	58	397,428	1,044,907	0	1,442,335	52
14	306	57	388,765	1,038,980	0	1,427,745	44
15	306	57	388,765	1,038,980	0	1,427,745	45
16	308	53	356,561	1,066,722	0	1,423,283	44
17	302	57	370,523	1,054,105	0	1,424,628	44
18	296	57	369,621	1,054,398	0	1,424,019	52
19	303	56	373,551	1,048,404	0	1,421,955	52
20	296	56	370,251	1,063,347	0	1,433,598	51
21	291	56	396,388	1,038,717	0	1,435,105	43
22	289	58	418,345	1,025,620	0	1,443,965	43
23	298	57	360,436	1,056,402	0	1,416,838	44
24	298	56	374,547	1,045,787	0	1,420,334	44
25	292	54	336,103	1,081,120	0	1,417,222	43
26	296	58	360,375	1,061,071	0	1,421,446	51
27	294	56	376,242	1,051,038	0	1,427,279	55
28	305	55	352,623	1,073,614	0	1,426,237	52
29	303	56	364,897	1,064,761	0	1,429,658	44
30	307	55	337,124	1,093,958	0	1,431,083	45
31	300	58	377,039	1,050,775	0	1,427,814	44
32	299	57	360,610	1,067,058	0	1,427,668	44
33	304	57	385,567	1,033,284	0	1,418,851	46
34	299	55	373,314	1,044,944	0	1,418,258	44
35	298	57	378,013	1,052,984	0	1,430,997	44
36	298	55	340,919	1,102,188	0	1,443,108	44
37	299	60	390,479	1,041,919	0	1,432,398	53
38	292	59	368,429	1,071,128	0	1,439,557	43
39	298	58	376,361	1,060,162	0	1,436,523	44
40	303	56	384,765	1,029,755	0	1,414,519	44
41	297	54	346,719	1,067,816	0	1,414,535	43
42	291	55	368,728	1,068,903	0	1,437,630	52
43	288	55	381,031	1,067,640	0	1,448,671	50
44	295	57	361,996	1,062,975	0	1,424,971	50
45	293	56	369,248	1,061,751	0	1,430,998	48
46	290	56	361,383	1,077,458	0	1,438,841	43
47	294	54	357,316	1,070,795	0	1,428,111	52
48	287	54	372,966	1,057,200	0	1,430,166	43
Average	297	56	369,584	1,059,539	0	1,429,123	47

Effects of the potential landing grid mesh sizes

Results for the first part are shown in Table 1. Decreasing the grid mesh size increases the number of potential landing locations and allows the model to find better solutions. The 640 m × 640 m grid mesh size leads to a potential reach zone containing only 3927 trees. The penalty of 3 unassigned trees (15,000) in Table 1 is mainly due to potential landing grid locations rather than to landing selection.

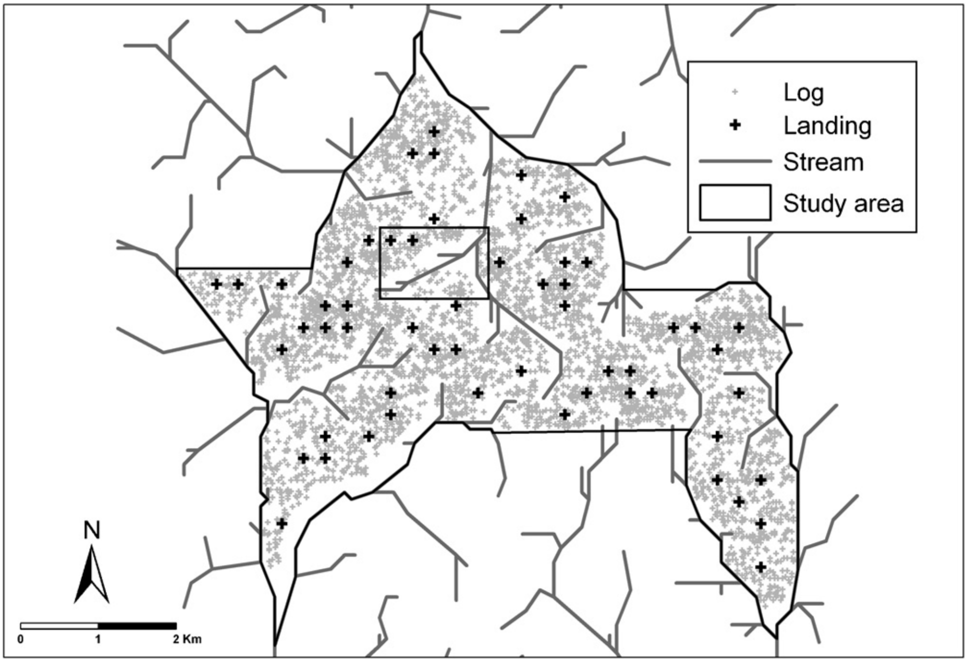

Fig. 2. Landing location for the best solution among the 48 test problem and outline of the Fig. 1.

A grid mesh size of 280 m × 280 m was the lower limit allowing CPLEX® to run on the workstation without an 'out of memory' running time error. Decreasing the grid mesh size also increases the processing time needed because the BIPM becomes larger. When the grid mesh size decreased from 700 m × 700 m to 280 m × 280 m, the processing time taken increased from 5 s to 42 s.

Effects of the first potential landing location

The 48 test problems in this part of the computational experiment are derived from the problem with the initial 280 m × 280 m grid mesh size by moving the first potential landing location in a 280 m × 280 m square window. Results for these test problems are presented in Table 2.

There is a 2.4% difference in the total costs between the worst (No. 8 with a total cost of 1,449,126) and the best (No. 40 with a total cost of 1,414,519) solutions. Analysing some potential landing grid with the same grid mesh size and selecting the best solution may slightly decrease the total cost and forest damages. CPLEX® takes from 42 s to 56 s to solve a BIPM in this part of the computational experiment. Although there is a pretty large difference in the processing time taken, there does not appear to be any relationship between the solution quality and the processing time.

Fig. 2 illustrates the landing locations of the best solution found for the 280 m × 280 m grid mesh size. The figure shows that the landings are located far from the streams and on locations with relatively high elevations in a coherent and realistic configuration.

Comparison with the manual planning method

The mean solution of the 48 test problems found using the BIPM is compared to that of the manual planning method executed by an experienced operator. The operator did not use any distance calculation or hauling cost in his landing site selection. His work was based on the locations of the trees, field mapped rivers and a 1/200.000 topographic map, as used in current practice.

Table 3
Results for manual planning and BIPM.

Method	No. of landings selected	Total opening cost (m)	Total hauling cost (m)	Total penalty (m)	Total cost (m)	No. of trees hauled	Average hauling cost (m)	Average number of log per landing
Manual	48	505,521	1,287,930	150,000	1,943,452	3900	330.2	81
BIPM	56	369,584	1,059,539	0	1,429,123	3930	269.6	70

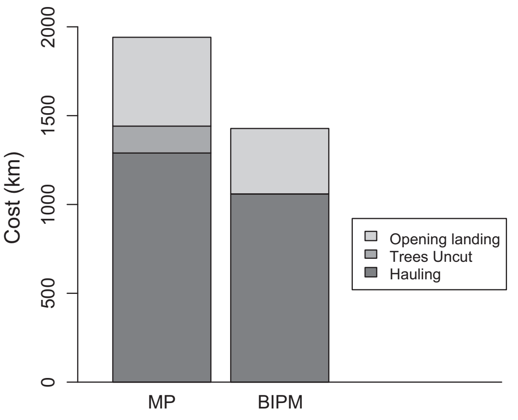

Fig. 3. Distribution of total cost of manual planning and BIPM solutions.

Compared to manual planning landing locations, the BIPM reduces the total cost by about 26%. The distributions of the total cost divided into landing opening cost, hauling cost and uncut tree penalties for both methods are shown in the stacked bar chart in Fig. 3.

Compared to the manual planning solution, the mean skidding distance is shorter and each landing receives fewer logs in the BIPM solution, as shown in Table 3. Although the BIPM solution increased the number of opened landings, the average and total landing opening costs are still lower and consequently the BIPM solution reduces damages to the forest.

Discussion

Field constraints

In other countries, like in Gabon, the field may be hilly. In such cases, the parameters in the model may need to be modified to adapt constraints such as decreasing the maximum hauling distance to 800 m or increasing candidate landing density to increase the likelihood of finding landings on ridge tops. The final landing locations are always dependent on local field constraints and may be slightly different from those proposed by any model whatever the potential landing grid mesh sizes are.

Method limitations

Working with a potential landing grid mesh size under 280 m × 280 m in this case study excludes the use of CPLEX® on the personal workstation used in this study. When the number of potential landing locations increases and/or when the model is applied to a wider area, like in Congo where annual logging zones often exceed 5000 ha, the BIPM may become very large. Trying different landing grid mesh sizes for different parts of the covered area with different tree densities may keep the BIPM within manageable size. When a BIPM becomes too large, an exact solution method, such as branch-and-cut used in CPLEX®, may not be able to solve it. In these cases, a heuristic method, such as tabu search (Sun, 2006), would be more useful than an exact method.

Conclusions

In this paper, a BIPM was proposed for the LLP. This model takes into account low-impact logging standards and legal constraints through a specific study layout elaboration. The CPLEX® software was used to solve the BIPM. The BIPM finds the best number and locations of landings for the selective logging in order to minimize the total cost of the landing opening and log hauling operations. Testing this model on a study area in Cameroon led to a better solution than that of manual planning while respecting low-impact logging standards and field applicability/constraints. This model is a first step in the optimization of selective logging applied to the Central African context which slowly progresses to near sustainable management and responsible logging.

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References

Akay, A.E., Karas, I.R., Sessions, J., Yuksel, A., Bozali, N., Gundogan, R., 2004. Using high-resolution digital elevation model for computer-aided forest road design. In: Proceedings of the 20th ISPRS Congress, Istanbul, Turkey, 12–13 July, p. 2004.

Anderson, A.E., Nelson, J., 2004. Projecting vector-based road networks with a shortest path algorithm. Can. J. Forest Res. 34, 1444–1457.

Bertault, J.-G., Sist, P., 1997. An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. Forest Ecol. Manage. 94, 209–218.

Contreras, M., Chung, W., 2007. A computer approach to finding an optimal log landing location and analyzing ground influencing factors for ground-based timber harvesting. Can. J. Forest Res. 37, 276–292.

Cornujélos, G., Nemhauser, G.L., Wolsey, L.A., 1990. The uncapacitated facility location problem. In: Mirchandani, P.B., Francis, R.L. (Eds.), Discrete Location Theory. Wiley, New York, pp. 119–171.

Dean, D., 1997. Finding optimal routes for networks of harvest site access roads using GIS-based techniques. Can. J. Forest Res. 27, 11–22.

Dijkstra, E.W., 1959. A note on two problems in connection with graphs. Numer. Math. 1, 269–271.

Durrieu De Madron, L., Forni, E., 1998. Les techniques d'exploitation à impact réduit en forêt dense humide africaine. Rapport technique CIRAD-Forêt, Montpellier, France.

Epstein, R., Sessions, J., Sapunar, P., Bustamante, F., Musante, H., 2001. PLANEX: A system to identify landing location and access. In: Proceedings of the International Mountain Logging and 11th Pacific Northwest Skyline Symposium, Seattle, WA, 10–12 December 2001. College of Forestry, University of Washington, Seattle, WA, pp. 190–193.

Freycon, V., Yandji, E., 1998. Le SIG, une aide pour tracer un réseau de pistes forestières: méthode et résultats. Rapport technique CIRAD-Forêt, Montpellier, France.

Hammami, A., 2003. Modélisation technico-économique d'une chaine logistique dans une enterprise réseau. Ph.D. Thesis, Univ. Laval, Québec, Canada. 395 pp.

Johns, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. Forest Ecol. Manage. 89, 59–77.

Liu, K., Sessions, J., 1993. Preliminary planning of road systems using digital terrain models. J. Forest Eng. 4, 27–32.

Murray, A.T., 1998. Route planning for harvest site access. Can. J. Forest Res. 28, 1084–1087.

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

Reutebuch, S.E., 1988. Routes: a computer program for preliminary route location. USDA For. Serv. Gen. Tech. PNW-GTR-216.

Sist, P., 1998. Directives pour l'application des techniques d'exploitation à faible impact (EFI) au Gabon: objectifs, principes et enjeux. In: Séminaire FORAFRI, Libreville, Gabon, 12–16 October 1998.

Sist, P., 2000. Les techniques d'exploitation à faible impact. Bois Forêts Trop. 265, 31–40.

Sun, M., 2006. Solving the uncapacitated facility location problem using tabu search. Comput. Oper. Res. 33, 2563–2589.