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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.

Keywords : landing location, uncapacitated facility location, Central Africa, road planning

JEL classification: C61, C02

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1. 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, 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 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 30m of streams and sources. Since hauling operations are expensive and destructive, the maximum hauling distance is limited to 1000m 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 Session, 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.

2. 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 $f_j > 0$, $\forall j \in J$ 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 $c_{ij} = \overline{c}$, with $\overline{c} >> \hat{c}$, 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:

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

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

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

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

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

A log i can't 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 uncapacitated facility location problem (UFLP). It is different from the UFLP model in two ways. In the UFLP model, each customer is assigned to exactly one facility, i.e., the constraint in (2) is of the form

$\sum_{j=1}^{n} x_{ij} = 1, \forall i \in I$ (Cornuéjols, 1990). The standard UFLP model also does not have the penalty term in the objective function (1).

3. 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.

3.1. Study area and dataset

The study area covered 2562 hectares of moist semi-deciduous tropical forest in Southeast Cameroon (3°48’37’’ E; 3°08’14’’ N) where the altitude varies between 550m and 650m. 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 90m 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.

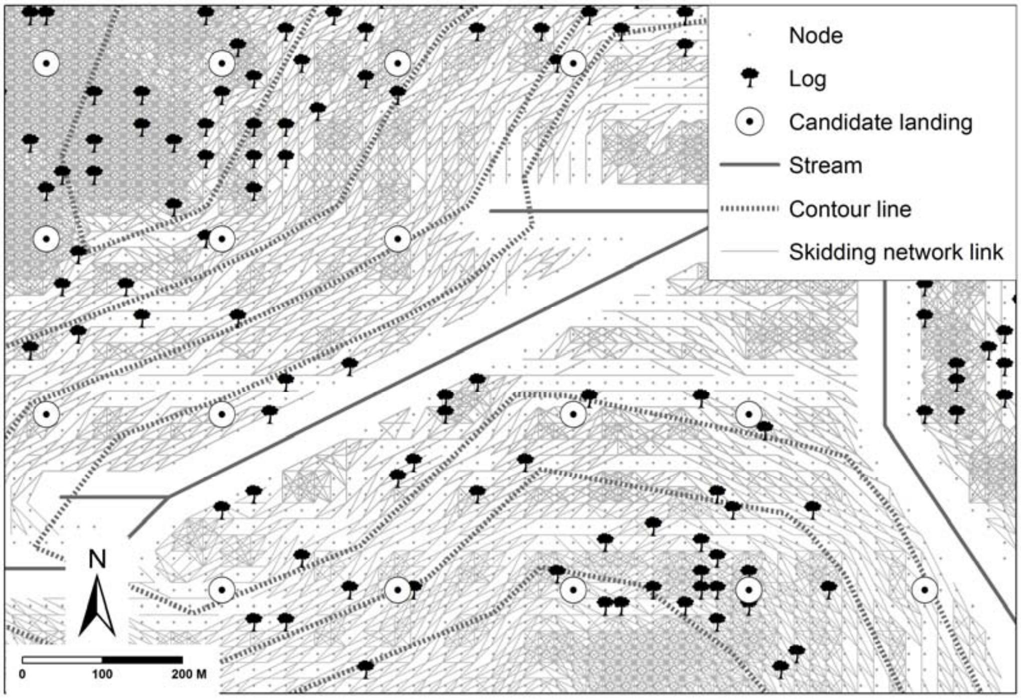
3.2. Skidding network design and candidate landing set

The area to be harvested is partitioned into a $20\text{m} \times 20\text{m}$ 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 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 $c_{ij} = \overline{c}$.

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 $100\text{m}\times100\text{m}$ is a sub grid of the initial $20\text{m}\times20\text{m}$ grid extracted by regularly selecting one node out of 25. The area partitioning is represented in figure 1.

Figure 1: Study area partitioning



3.3. Landing opening costs and log skidding cost matrix

For each candidate landing j, an initial opening cost of 2500m 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 1000m 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 2500m 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 2500m (best or cheapest location) and 27500m (worst or most expensive location).

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

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

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 is no competitive landings, 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 (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 $c_{ij} = \overline{c}$ is assigned to a path that is prohibited by the reduced-impact logging standards and stream crossings. In this case study, $\overline{c} = 5000$ 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.

3.4. 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 (particulary 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 5000m, i.e., $\alpha = 5000$ in the objective function (1).

4. 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 a 3.2Ghz Pentium processor. 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.

4.1. 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 640m grid mesh size leads to a potential reach zone containing only 3927 trees. The penalty of 3 unassigned trees (15000) in table 1 is mainly due to potential landing grid locations rather than to landing selection. A grid mesh size of 280m 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 700m to 280m, the processing time taken increased from 5 seconds to 42 seconds.

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 (sec.)
700	45	33	443333	1441801	0	1885134	5
640	51	38	397946	1273715	15000	1686661	6
580	67	34	326220	1353848	0	1680068	8
520	80	38	370714	1256353	0	1627067	9
460	103	45	390297	1178994	0	1569291	11
400	131	46	336699	1188344	0	1525043	15
340	183	52	397798	1086852	0	1474650	26
280	294	56	360755	1080217	0	1440972	42
220	830			OUT OF MEMORY			
160	2134			OUT OF MEMORY			

4.2 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 280m grid mesh size by moving the first potential landing location in a $280\text{m} \times 280\text{m}$ square window. Results for these test problems are presented in Table 2.

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

Solution ID	No. of potential landings	N of landings selected	Total opening cost (m)	Total hauling cost (m)	Total penalty (m)	Total cost (m)	Processing time (sec.)
1	294	56	360755	1080217	0	1440972	42
2	298	55	363336	1061823	0	1425159	43

3	288	56	372032	1054164	0	1426196	42
4	291	54	325017	1096238	0	1421256	43
5	289	55	345120	1079777	0	1424897	50
6	286	55	381379	1048379	0	1429759	42
7	300	58	410162	1034619	0	1444782	44
8	297	54	376244	1072882	0	1449126	53
9	311	56	364233	1055204	0	1419437	45
10	299	58	368624	1056434	0	1425058	43
11	299	54	343019	1083762	0	1426781	56
12	301	58	382695	1043694	0	1426388	51
13	297	58	397428	1044907	0	1442335	52
14	306	57	388765	1038980	0	1427745	44
15	306	57	388765	1038980	0	1427745	45
16	308	53	356561	1066722	0	1423283	44
17	302	57	370523	1054105	0	1424628	44
18	296	57	369621	1054398	0	1424019	52
19	303	56	373551	1048404	0	1421955	52
20	296	56	370251	1063347	0	1433598	51
21	291	56	396388	1038717	0	1435105	43
22	289	58	418345	1025620	0	1443965	43
23	298	57	360436	1056402	0	1416838	44
24	298	56	374547	1045787	0	1420334	44
25	292	54	336103	1081120	0	1417222	43
26	296	58	360375	1061071	0	1421446	51
27	294	56	376242	1051038	0	1427279	55
28	305	55	352623	1073614	0	1426237	52
29	303	56	364897	1064761	0	1429658	44
30	307	55	337124	1093958	0	1431083	45
31	300	58	377039	1050775	0	1427814	44

32	299	57	360610	1067058	0	1427668	44
33	304	57	385567	1033284	0	1418851	46
34	299	55	373314	1044944	0	1418258	44
35	298	57	378013	1052984	0	1430997	44
36	298	55	340919	1102188	0	1443108	44
37	299	60	390479	1041919	0	1432398	53
38	292	59	368429	1071128	0	1439557	43
39	298	58	376361	1060162	0	1436523	44
40	303	56	384765	1029755	0	1414519	44
41	297	54	346719	1067816	0	1414535	43
42	291	55	368728	1068903	0	1437630	52
43	288	55	381031	1067640	0	1448671	50
44	295	57	361996	1062975	0	1424971	50
45	293	56	369248	1061751	0	1430998	48
46	290	56	361383	1077458	0	1438841	43
47	294	54	357316	1070795	0	1428111	52
48	287	54	372966	1057200	0	1430166	43
Average	**297**	**56**	**369584**	**1059539**	**0**	**1429123**	**47**

There is a 2.4% difference in the total costs between the worst (No. 8 with a total cost of 1449126) and the best (No. 40 with a total cost of 1414519) 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 seconds to 56 seconds 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.

Figure 2 illustrates the landing locations of the best solution found for the 280m 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.

4.3. 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.

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 figure 3.

Figure 2 : Landing locations for the best solution among the 48 test problems

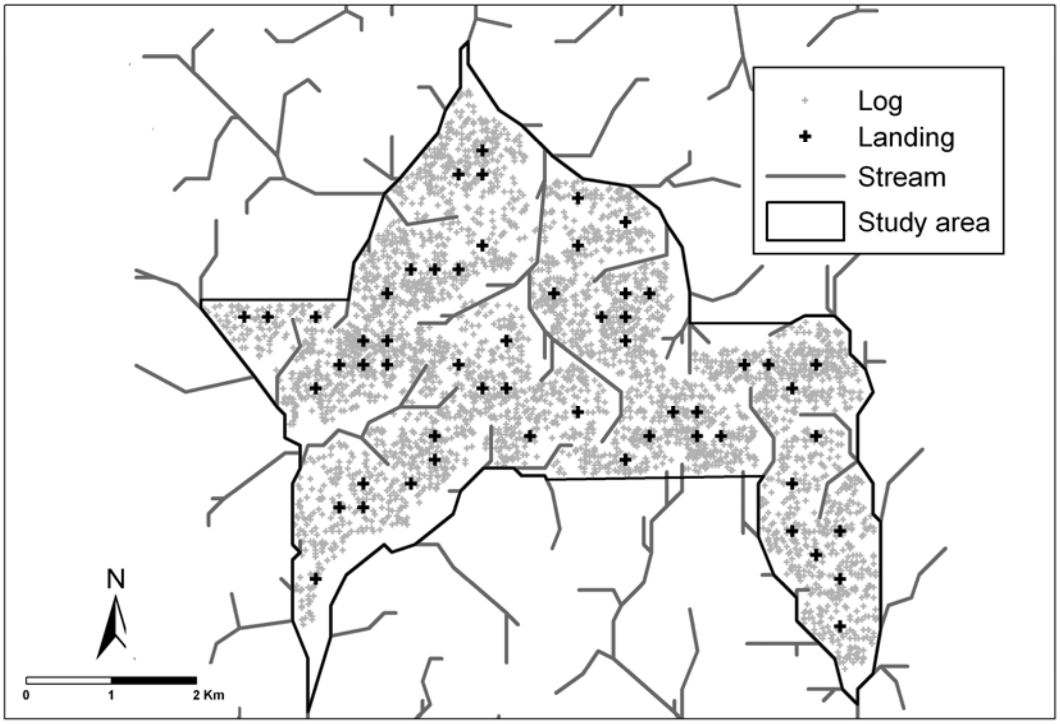


Table 3 : Results for manual planning and BIPM

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	3 900	330.2	81
BIPM	56	369 584	1 059 539	0	1 429 123	3 930	269.6	70

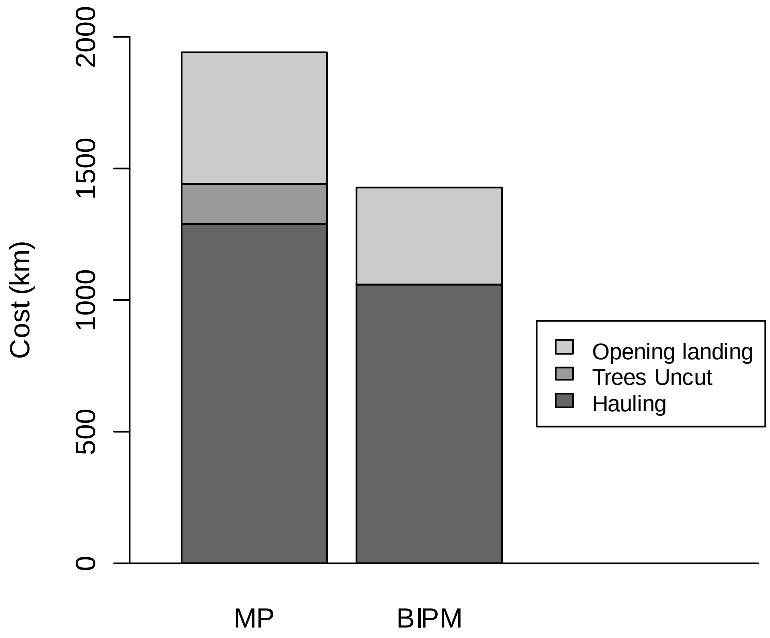
Compared to the manual planning solution, the mean skidding distance is shorter and each landing receives a larger number of logs in the BIPM solution. Although the BIPM solution increased the number of opened landings, the average and global landing opening costs are still lower and consequently the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

5. Discussion

5.1. 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 800m 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.

Figure 3: Distribution of total cost of manual planning and BIPM solutions



5.2. Method limitations

Working with a potential landing grid mesh size under 280m in this case study excludes the use of CPLEX® on most personal computers. 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 hectares, 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.

6. 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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