Optimizing scheduling and routing of forest harvesting equipment

Víctor Viana
Sede Tacuarembó, Universidad de la República, Uruguay
vviana@cut.edu.uy

Héctor Cancela
Facultad de Ingeniería, Universidad de la República, Uruguay
cancela@fing.edu.uy

Lorena Pradenas-Rojas
Departamento de Ingeniería Industrial, Universidad de Concepción, Chile.
lpradena@udec.cl

ABSTRACT

The management of the forest resources involves decision making at strategic, tactical, and operational levels. One of the components of this decision making chain corresponds to forest harvesting, which is a step of vital importance because of its high impact on production costs. In Uruguay, almost 75 % of the total forestry operations destined to the production of pulp are in charge of contractor companies. This work aims to optimize the scheduling and routing of the contractors' harvesting equipment, which must be relocated between the places to be harvested in a season. This work proposes a combinatorial optimization model for this problem, based on the Multi Depot Multiple Traveling Salesman Problem (MmTSP). This model can then be used as an efficient and practical tool for helping to develop the annual forest harvesting scheduling and equipment allocation for contractor companies, leading to better quality plans and improvement opportunities.

KEYWORDS. Optimization. Scheduling. Forestry.

https://proceedings.science/p/85489?lang=pt-br

1.Introduction

In recent years, the Uruguayan forestry sector has taken a big boost, due in particular to the development of the pulp industry in the country. Cellulose production has gone from contributing 0.2% of the country's GDP in 2006 to 1.3% in 2015 [Tommasino and Annunziatto 2015]. Cellulose is one of the main products that Uruguay currently exports, generating an important demand for wood as a raw material for this industry. The annual consumption estimated is 8.5 million m^3 of wood to make cellulose pulp, and in the next 15 years, it is estimated that more than 10 million m^3 will be consumed on average per year, which makes it feasible to install more factories for this product [Dieste 2012].

There are nevertheless different factors that cause logistical problems and challenges in this sector:

- main road paths very far from large forest plantations;
- secondary routes in poor condition;
- scarce use of the rail transport.

In Uruguay, the distance between pulp mills and tree plantations exceeds 200 kilometers in most cases. The costs involved in transporting wood to pulp plants are high, reaching 70% of the entire production chain [Gamio 2016].

Forest planning is a highly complex decision-making problem involving the participation of various factors: ecological, productive and economic systems [Weintraub and Romero 2006] [Milanesi et al. 2014] [Broz et al. 2016]. The management of the forest resources involves decision making at strategic, tactical, and operational levels, with both short and long term consequences. One of the components of this decision making chain corresponds to forest harvesting, which is a step of vital importance because of its high impact on production costs.

An efficient planning of harvesting operations can significantly lower costs associated with logistics and improve the economic performance of companies in the sector. In Uruguay, almost 75 % of the total forestry operations destined to the production of pulp are in charge of contractor companies, which are an important player in the supply chain.

The trees can be harvested after they reach the age of eight years. There are some large pulp companies, which are also owners of most of the tree plantations, and who have agreements with contractor companies to carry out the harvesting. Each contractor company is assigned an annual harvest plan consisting of a series of plantations which it must visit and harvest the areas requested, committing in each case to:

- perform that harvest plan in a certain period of time,
- deliver a given volume of wood in each period of the plan.

At each visit to the harvesting areas or blocks, the contractors have to locate the necessary equipment to carry out the cutting and loading operation. The contractors may decide the order in which to visit the plantations; an efficient choice should minimize the transfer costs of the equipment between the harvest sites. Moreover, each harvesting equipment belonging to a contractor starts its journey from a base of operations of that company; and it returns there once the whole harvest is finished.

This work aims to optimize the scheduling and routing of the contractors' harvesting equipment, which must be relocated between the places to be harvested in a season.

2.Main Objectives

The main motivation for this work is to optimize the sequence in which the contractors perform the harvest, in order to minimize the costs of equipment displacement between sites.

In order to achieve this goal, the following specific objectives were defined:

1. Formulate, solve and evaluate a mathematical model for supporting decision-making in the allocation to a forest contractor company of the farms to harvest during a year and in the definition of the harvest planning details.
2. Implement computationally the formulated model.

https://proceedings.science/p/85489?lang=pt-br

3. Generate a set of structured instances, based on real data, to evaluate the proposed model and to contribute to the decision making at the tactical planning level.

3.Mathematical Model

This work proposes a combinatorial optimization model for this problem, based on the Multi Depot Multiple Traveling Salesman Problem (MmTSP) [Kara and Bektas 2006].

Model indices: next, the sets and the input data are described.

- F: Set of contractor bases of operations.
- B: Set of blocks (land) to harvest in the year.
- T: Set of time units in which each block is to be harvested.

Model parameters: next, we will identify the parameters of the problem, where the costs associated with the transfer of harvesting equipment between the different places.

- C_{ij}: displacement cost between the harvest block or base of operations, with $i, j \in F \cup B$.
- m_f: is the amount of harvesting equipment belonging to a forestry contractor, $f \in F$.
- $Tmin_i$: is the time in which the block i can start to be harvested.
- $Tmax_i$: is the maximum time where the i block can be harvested.
- L: the maximum number of blocks harvesting equipment can visit.
- M: the minimum number of blocks harvesting equipment can visit.
- D_t : is the total demand for wood in each in time t.
- v_i: is the volume of wood available in each harvest block i.

Model variables: we are interested in identifying the optimal harvest sequence for each team belonging to a forestry contractor. Therefore, we define the binary variable x^f_{ij} as:

$$x_{ij}^f = \begin{cases} 1, \text{ if a harvest equipment of the base } f \text{ moves from the place } i \text{ to } j \\ 0, \text{ otherwise} \end{cases} \quad i, j \in F \cup B \tag{1}$$

We define the binary variable y^t_i as:

$$y_i^t = \begin{cases} 1, \text{ if a block } i \text{ is harvested in time } t \\ 0, \text{ otherwise} \end{cases} \tag{2}$$

The integer variable u_i represents the number of blocks visited when a harvest equipment visits block i.

Target: our main purpose is to minimize the costs of moving equipment between harvest blocks, and of their transfer between the harvest blocks and the bases of operations. We define as the objective function the total cost of the transfers between the different harvest blocks and the bases of operations.

$$min \sum_{f \in F} \sum_{i \in B} (C_{fi} x_{fi}^f + C_{if} x_{if}^f) + \sum_{f \in F} \sum_{i \in B} \sum_{j \in B} C_{ij} x_{ij}^f \tag{3}$$

Initial constraints:

- he m_f harvesting equipments start from each one of the respective bases of operations.
- each harvest block is visited by a single harvesting equipment.

https://proceedings.science/p/85489?lang=pt-br

- the team that visits a block comes from a different place, and moves to another block or base of operations.

$$\sum_{i \in B} x_{fi}^{f} = m_f, \forall f \in F \tag{4}$$

$$\sum_{f \in F} \sum_{i \in B \bigcup F, i \neq j} x_{ij}^{f} = 1, \forall j \in B \tag{5}$$

$$\sum_{i \in B \bigcup F, i \neq j} x_{ij}^{f} - \sum_{i \in B \bigcup F, i \neq j} x_{ji}^{f} = 0, \forall j \in B \tag{6}$$

Limit constraints:

- L is upper limits and M is lower limits are imposed on the number of blocks visited by each harvesting equipment..
- u_i = 1 if and only if *i* is the first block in the tour for any team, provided that *M* >= 2.

$$u_i + (L-2) \sum_{f \in F} x_{fi}^{f} - \sum_{f \in F} x_{if}^{f} \leq L - 1, \forall i \in B \tag{7}$$

$$u_i + \sum_{f \in F} x_{fi}^{f} + (2-M) \sum_{f \in F} x_{if}^{f} \geq 2, \forall i \in B \tag{8}$$

The restrictions (7) and (8) can be called limit restrictions, since they impose upper and lower limits on the number of blocks that each collection team visits.

Restrictions of sub-tours:

- restrictions of single site tours: it is forbidden for a vehicle to visit only one block starting from a base of operations, and return to it immediately (redundant if *M* >= 2)
- the sub-tours of the formulation are eliminated

$$\sum_{f \in F} x_{fi}^{f} + \sum_{f \in F} x_{if}^{f} \leq 1, \forall i \in B \tag{9}$$

$$u_i - u_j + L \sum_{f \in F} x_{ij}^{f} + (L-2) \sum_{f \in F} x_{jf}^{f} \leq L - 1, \forall i \in B, \forall j \in B, i \neq j \tag{10}$$

With the restriction (10) it is ensured that $u_j = u_i + 1$ if and only if $x^f_{ij} = 1$. Therefore, the formation of any sub-route between the nodes in B is prohibited.

Time windows constraints and demand constraints:

$$u_i \geq Tmin_i, \forall i \in B \tag{11}$$

$$u_i \leq Tmax_i, \forall i \in B \tag{12}$$

https://proceedings.science/p/85489?lang=pt-br

$$\sum_{t \geq Tmin_i}^{t \leq Tmax_i} y_i^t = 1, \forall i \in B \quad (13)$$

$$u_i = \sum_{t \geq Tmin_i}^{t \leq Tmax_i} t y_i^t, \forall i \in B \quad (14)$$

$$\sum_{i \in B} y_i^t v_i \geq D_t, \forall t \in T \quad (15)$$

The problem MmTSP are NP-Hard [Kota and Jármai 2013]. It is easy to reduce our problem to MmTSP, since taking $Tmin_i = 1$ and $Tmax_i = |B|$ for all i (also $v_i=0$ for all i and $D_t = 0$ for all t), we have an instance of our problem that is an instance of MmTSP. If we can find a solution to our problem in polynomial time, we can also find a polynomial time solution for MmTSP, therefore the problem we are dealing with is as difficult as the MmTSP, it is also NP-Hard.

According to the definitions of the variables x^f_{ij}, y_i and u_i, seen above, we can say that the total quantity of the variables of the problem is of the order $O(variables) = O(variable\ x) + O(variable\ y) + O(variable\ u) = O(|B| * |B| * |F|) + O(|B| * |T|) + O(|B|) = O(|B|^2 * |F|)$. Taking into account the family of constraints defined (from (4) to (15)), the number of constraints of the problem is of the order of $O(restrictions) = \Sigma^{i=12}_{i=1} O(restriction_i) = O(|B|)$.

3.Results

The model is implemented in a script using the AMPL modeling language, we use the solver CPLEX version 12.6.3.0. The model was executed on a server with CentOS Linux operating system release 7.2.1511 (Core), 64 bit, with 8 Intel R Core TM i7 processors and 15 GB of RAM. To obtain test data, the Digital Forestry Cartography published by MGAP in 2012 was used [MGAP 2012]. The maps were georeferenced using QGIS [QGIS 2018] and the coordinates of the main forest plantations in Uruguay were obtained from each map. Then, to form the data sets, some of these plantations were raffled with uniform distribution. The distance calculations are made using the Google Maps API [Google Map API 2018], a Python script was programmed to obtain from this source the distance matrix between the harvest points and the bases of operations.

Setting 1

As a first test case (Case 1), in order to test the model, 12 random harvest points were chosen in the department of Tacuarembó (Uruguay), and a base of operations located in the capital city. The data of these blocks can be seen in Table 1, where each of these points corresponds to a forest plantation of the species Eucalyptus or Pine. For this configuration, 2 harvest teams are chosen. Both the time window for the harvest of each block, and the estimated volume of wood in each, were also fixed at random.

Block	Time windows for harvest	Wood volume (m^3)
1	2-5	18894
2	1-4	12580
3	1-4	11796
4	2-5	8796
5	2-5	18041

https://proceedings.science/p/85489?lang=pt-br

6	3-6	18303
7	3-6	15379
8	1-4	9072
9	1-4	11023
10	3-6	9651
11	1-4	13455
12	3-6	17015

Tab. 1 : Data of the harvest blocks of Case 1.

For this case, a monthly wood demand of 22000 m^3 was established. The optimal route obtained can be seen in Figure 1, with a total length of 679 km.

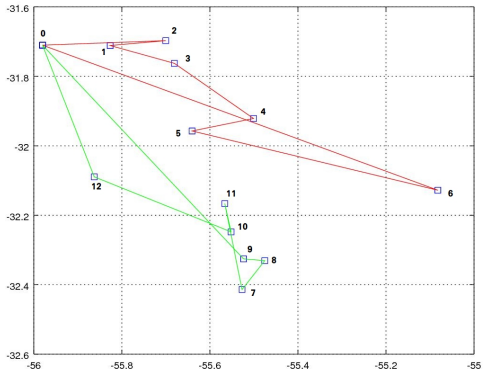


Fig. 1: Routes of the two harvest teams for Case 1.

Similar to Case 1, 15 harvest points are chosen in the department of Rivera, the base of operations located in the capital of that department, and two equipment available for harvesting (Case 2). The data of each block can be seen in Table 2 and the route obtained in Figure 2 of a total length of 862 km. In this case, a demand of 12578 m^3 per month is configured.

Block	Time windows for harvest	Wood volume (m^3)
1	5-6	12247
2	8-9	8673
3	7-8	11646
4	4-5	9104
5	1-2	16662
6	1-2	12455
7	6-7	14758
8	5-6	8496
9	2-3	11823
10	3-4	11705

https://proceedings.science/p/85489?lang=pt-br

11	3-4	12726
12	4-5	15761
13	7-8	15315
14	2-3	13837
15	6-7	13458

Tab. 2 : Data of the harvest blocks of Case 2.

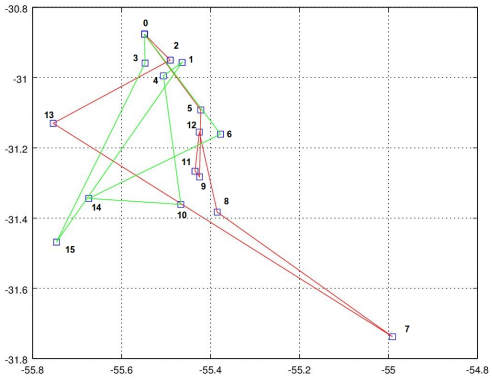


Fig. 2: Routes of the two harvest teams for Case 2.

Setting 2

For this case, Cases 1 and 2 are considered in an integrated manner, that is, the model is executed for a scenario composed of the bases and harvest blocks of the previous cases. For this case, they have 2 bases of operations and 27 blocks of harvest. The routes of the 4 harvest teams can be seen in Figure 3. The total length of the runs of these coefficient teams is 1373 km (168 km less than the separate execution of the two cases, a 10.9% saving).

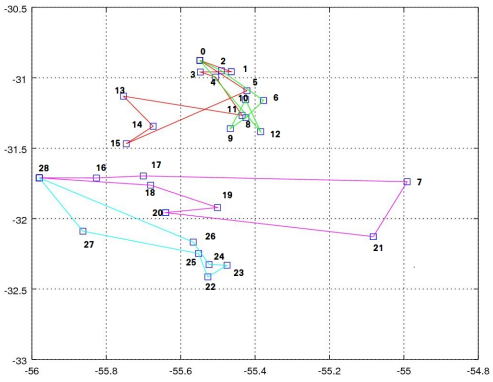


Fig. 3: Routes of the two harvesting teams for Integrated Case 1 and Case 2.

Setting 3

For this setting, the example is taken of 11 contractors, each with their base of operations distributed throughout the country and harvesting equipment available. The 47 harvesting blocks were georeferenced, taking random different points with uniform distribution, similar to the cases seen before. This scenario is much greater than the previous ones, and corresponds to the

https://proceedings.science/p/85489?lang=pt-br

planning of a whole year of a forestry company. In terms of number of contractors and demands, it is an interesting case because it also shows the dispersion of the harvest in many contractors. Table 3 shows for each contractor, the amount of harvesting equipment of each one, and the number of kilometers traveled by them once the mathematical model applied to each case has been executed.

Contractor	Harvest equipment	Distance traveled (km)
A	3	550
B	1	281
C	1	194
D	3	885
E	2	582
F	2	292
G	1	458
H	1	323
I	1	514
J	1	166
K	2	408

Tab. 3: Case with 11 contractors with their respective bases of operations.

Then the model applied to groups of contractors is analyzed. First, an analysis is done grouping the contractors into three groups (depending on the proximity geographic among them), and then the model is applied to all contractors together. Table 4 shows the comparison of the distances traveled for each group of contractors in relation to the model applied individually.

Group of Contractors	Distance traveled separately (km)	Distance traveled in an integrated manner (km)
A, B, C, D	1910	1909
E, F, G, H	1655	1588
I, J, K	1088	1088
A, B, C, D, E, F, G, H, I, J, K	4653	4585

Tab. 4: Comparison of applying the model to each case separately and in an integrated way by group.

In all the scenarios reviewed, the application of the model in an integrated manner incurs savings of distances traveled compared that were made individually.

4.Conclusions and future work

In this work, we present a methodology for solving one problem arising in forest planning, namely the optimal sequencing and routing of forest harvesting equipment.
This particular problem is relevant in the Uruguayan context, as contractor companies work on behalf of cellulose pulp industries and must reduce their operational costs in order to improve their efficiency when planning the wood harvest of the assigned plantations.

https://proceedings.science/p/85489?lang=pt-br

The mathematical programming model developed is able to represent the planning problem stated, and can be implemented to provide solutions based on real data. A number of realistic size instances were generated, based on real geographical data of operations bases and plantations locations, showing that the model can be used in practice. Also, the experiments performed allow to estimate the improvements that could be attained if different contractor companies coordinate their work and plan jointly their schedules and operations. This model can then be used as an efficient and practical tool for helping to develop the annual forest harvesting scheduling and equipment allocation for contractor companies, leading to better quality plans and improvement opportunities.

Future work can take into account other aspects, such as disruptions in plans due to unexpected equipment failures, or difficulties to access some plantations due to heavy rains that make some roads impossible to use during part of the year. Also, it would be interesting to be able to obtain real data from companies regarding past harvest plans (defined manually by the contracters) and compare them with the results of the mathematical programming models.

References

Tommasino, H. and Annunziatto, W. (2015) Situación de la cadena forestal, con énfasis en la celulosa, tech. rep., *Oficina de Planificación y Política Agropecuaria, Ministerio de Ganadería, Agricultura y Pesca*. Web page: http://www.mgap.gub.uy/sites/default/files/situacion_de_la_cadena_forestal_con_enfasis_en_la_celulosa.pdf. Accessed 2018-06-01.

Dieste, A. (2012) Programa de promoción de exportaciones de productos de madera, tech. rep., *Dirección Nacional de Industrias, Ministerio de Industrias, Energía y Minería, Consejo Sectorial Forestal-Madera*, Web page: http://www.adimau.com.uy/articulos/07_programa_de_promocion_de_exportaciones_de_productos_de_madera_2012.pdf. Accessed 2018-06-01.

Gamio, P. (2016) El precio de la competitividad, *Revista Forestal*, (14), pp. 36–41.

Weintraub, A. and Romero, C. (2006) Operations research models and the management of agricultural and forestry resources: a review and comparison. *Interfaces*, 36(5), pp.446-457.

Milanesi, G. S., Broz, D., Tohmé, F. andRossit, D. (2014). Strategic analysis of forest investments using real option: The fuzzy pay-off model (FPOM). *Fuzzy Economic Review*, 19(1), pp. 33.

Broz, D., Durand, G., Rossit, D., Tohmé, F., Frutos, M. (2016). Strategic planning in a forest supply chain: a multigoal and multiproduct approach. *Canadian Journal of Forest Research*, 47(999), pp. 297-307.

Kara, I. and Bektas, T. (2006) Integer linear programming formulations of multiple salesman problems and its variations, *Omega*, 174, pp. 1449–1458.

Kota, L and Jármai, K. (2013). Preliminary Studies On The Fixed Destination Mmtsp Solved By Discrete Firefly Algorithm. Advanced Logistic Systems, 7(2), pp. 95–102.

MGAP (2012). Cartografía forestal. Web site http://www.mgap.gub.uy/unidad-ejecutora/direccion-general-forestal/informacion-tecnica/cartografia-forestal Accessed 2018-06-01.

QGIS Geographic Information System (2018). Open Source Geospatial Foundation Project. Web page: http://qgis.osgeo.org. Accessed 2018-06-01.

Google Map APO (2018). Distance matrix API. Web site: https://developers.google.com/maps/documentation/distance-matrix/start?hl=es-419 Accessed 2018-06-01 .