



AGRARIAN SCIENCES

Optimization of Wood Supply: The Forestry Routing Optimization Model

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Abstract: The main purpose of this paper was to present the Forestry Routing Optimization Model (FRoM) as a version of the classical Vehicle Routing Problem (VRP). This work approaches for wood logistic problems consisting of simple displacement and multiple displacements of trucks toward the stands. The FRoM encompasses both steps into one single integer mixed linear programming model, considering cranes and trucks schedule, fleet reduction, reduction of overtime, reduction of half-load transportation, and approaching the minimum distance traveled along a fixed planning horizon. Some technique constraints were implemented to provide accurate model function. An executed real problem data was used to compare the outcomes. The objective was to carry and transport 21,881.82 tons of lumber from 10 stands using a total of 48 trucks and 5 cranes in a planning horizon of 6 days, which each day has 20 hours of effective work. The FRoM has performed a fleet reduction of 72.92%, eliminating overtime. It has reduced the half-load trips to the order of 3.17% of all routes. The crane's analysis allowed catching points of inefficiency due to operational idleness. The FRoM provided savings of 49.12% at all logistic costs. FRoM has shown to be a good option as a route optimizer for forestry logistics.

Key words: combinatorial optimization, forest planning, forest logistic, mathematical modeling, timber transportation, vehicle routing problem.

INTRODUCTION

Innovation ability and its implementation into practice are crucial for the success of enterprises in traditional sectors such as forestry and in the context of countries with economies in transition (Štěrbová et al. 2019), especially when it comes to cost reduction in forestry activities.

Harvesting and forest transportation accounts for a large portion of the operating costs for forest companies and needs to be better managed (Epstein et al. 2007, Santos et al. 2016, Araújo Júnior et al. 2017). Moreover, it is not only about the relationship between costs and revenues, but also advances in aspects that affect all forest production system. For example,

19% of Norway's carbon dioxide emissions come from road transportation (Trømborg et al. 2009), which states the real need for optimized planning for the transportation activity. However, cost remains the main weight in this equation. Within this statement, forest harvesting costs involve the operational cost of the harvester tractor which corresponds to 23% of the fixed costs and 77% of the variable costs of the machine, based on fuel and periodic maintenance demand (Leite et al. 2013). The forwarder's operational cost is equals 20.88% of fixed costs, and 79.12% of variable costs. On the other hand, the transportation of this biomass corresponds, on average, to a third of the industrial production costs, playing the most

significant cost in the operational scale (Frisk et al. 2010), and therefore, they lack greater actions control.

The planning linked to optimization methods has been used in recent years, as observed in works involving vehicle routing (Cuda et al. 2015, Prodhon & Prins 2014, Koç & Karaoglan 2016, Li et al. 2015), log transportation (Borges et al. 2014, Bordón et al. 2018), queuing problem (Jain et al. 2012, Chun & Mitra 2014, Brooks et al. 2016), pattern recognition (Antonova 2011, Macas et al. 2014) and scheduling problem (Ramage et al. 2013, Giménez et al. 2013, Diaz-Balteiro et al. 2009, Diaz-Balteiro & Rodriguez 2006).

Within the theme involving vehicular routing, the Traveling Salesman Problem (TSP) is considered the foundation for the construction of a series of mathematical models, influencing the emergence of several related problems in the category of Vehicular Routing Problems (VRP), which is commonly used by companies in logistics transportation networks of goods. This type of problem is classified by Lenstra & Rinnooy Kan (1981) and Pierre & Zakaria (2017) as NP-hard, it means increased complexity of resolution and, depending on its complexity, they are not solved by an exact method in polynomial time. Therefore, extensive state-of-the-art works on VRP can be found in Laporte (2009) and Toth & Vigo (2014). Besides that, numerous resolution algorithms have been extensively tested in recent years (Nagy & Salhi 2007, Subramanian et al. 2012, Neto et al. 2013, Vopenka et al. 2015, Vidal et al. 2019, Andelmin & Bartolini 2019, Altabeeb et al. 2019, Ruiz et al. 2019).

The transportation planning of goods presents an approach which aims to aggregate political, economic, environmental, and social values, seeking to reduce future conflicts after decision making. Scientific contributions related to governance (Birben & Gençay 2019) and concept of sustainability in the forestry sector are

increasingly necessary, mainly with a diversified focus for the sustainable production of wood (Santos et al. 2019). Therefore, models regarding mathematical programming are already widely able to equate this scenario (Ananda & Herath 2009). The optimization of the wood supply chain has been raised in the scientific scenario, with a greater emphasis (Stepanov & Smith 2009, Fotakis et al. 2012).

The contributions of this study are related to the proposal of a forestry routing optimization model to solve complex forest logistics problems, which considers the most common technical restrictions in the forestry industry. Finally, we assume that we will provide management perspectives corresponding to the integration of processes and technologies for forestry planning operations.

The next challenge lies on the identification of robust methods for solving this category of mathematical problems which will assist decision-making (Weintraub et al. 1996, Flisberg et al. 2007, Carlsson & Rönnqvist 2007, Audy et al. 2012). Therefore, some questions are described for the construction of a decision support system, which are: Is there a mathematical model capable of generating an optimal response in a real world, since many models work only in the theoretical field? How to integrate fleet of trucks and the budget of cranes in logistic operation? Is it possible to build an integrated management system for forestry logistic? That been stated, the objective of this work was to describe the forestry logistic complexity as a case of vehicle routing problem and present a Forestry Routing Optimization Model to solve a real forestry case.

MATERIALS AND METHODS

This section of the paper shows the complexity of the problem under the forest point of view

and the strategies which were applied to turn this model closer to reality (*Section: Forestry Transportation Problem*); in the second section (*Section: Real-Case Data*) is showed the dimension of the applied forest case; the third section (*Section: Description of the Forest Routing Optimization Model*) introduces the model on its mathematical format; and the fourth part (*Section: Evaluation and Computings*) explained the metrics applied to evaluate the results.

Forestry Transportation Problem

The following problem brings a structure of a typical graph, where $V(G)$ is the non-empty set of vertices, $E(G)$ is the set of edges and ψ_G is the functional that associates each edge of the graph G with an ordered pair of vertices of G . In this typological relation, the stands and the factory are associated to vertices and, accordingly, the edges are assigned with the distances between them. The logistics operation in this graph is integrated with the formation of routes to transport the wood from the stands to the factory, following the connection of edges in the factory-stand-factory path. This description can be assigned to the classical vehicle routing approach. Although, the forest logistic system brings an atypical design to these approaches usually found in the literature. Classic VRP consists of a vehicle leaving the specific vertex (depot) to reach out a group of geographically dispersed consumers exactly once (Pierre & Zakaria 2017). However, in the forestry logistic system, the wood amount from selected block of stands is greater than the load capacity of a single truck. Therefore, the transportation of wood tends not to change (or Simple displacement) until a specific moment when there will be less remaining burden than the load capacity of a truck (the residual burden in the stand). At this moment, the possibility of connection between two stands comes over

as an efficient strategy (Multiple displacement). The fundamental analysis to be aware of is the problem interpretation. Many approaches for Vehicle Routing Problem consider the classic interpretation for modeling a scenario, although there are real-case data sets that do not follow this pattern, and the forest industry is one of them. It might be expressed as a case of VRP which approaches two different types of models onto one mathematical formulation.

The first approach to consider for solving the forest industry logistic system is a simple displacement, consisting of a direct displacement along the vertices connecting the factory and a specific stand. This action is executed several times by the trucks to withdraw the major amount of wood from the stand, supplying the factory (Figure 1a). This maneuver generally occurs due to the large quantity of lumber on a stand at the beginning of the operation. On the other hand, the multiple displacement reaches out when the residual burden achieves a wood amount which its sum fulfills the load capacity of a single truck. Thus, to take all the residual logs from more than one stand at the same trip, the truck plays a multiple travelling salesman role (Figure 1b).

Along all these steps, the cranes work as limiting factor due to the smaller fleet budget available to provide the loading of trucks, often causing queue situations, which produce lower operational yields. Additionally, the amount of time required for workers finishing the task must be considered due to affecting directly trucks and cranes' yield and, accordingly, the supply chain of wood. The FROm contemplates all these features working as a complete solver for forest logistics system.

Real-Case Data

A real scenario of a pulp company was provided, and this work introduced the Forest Routing

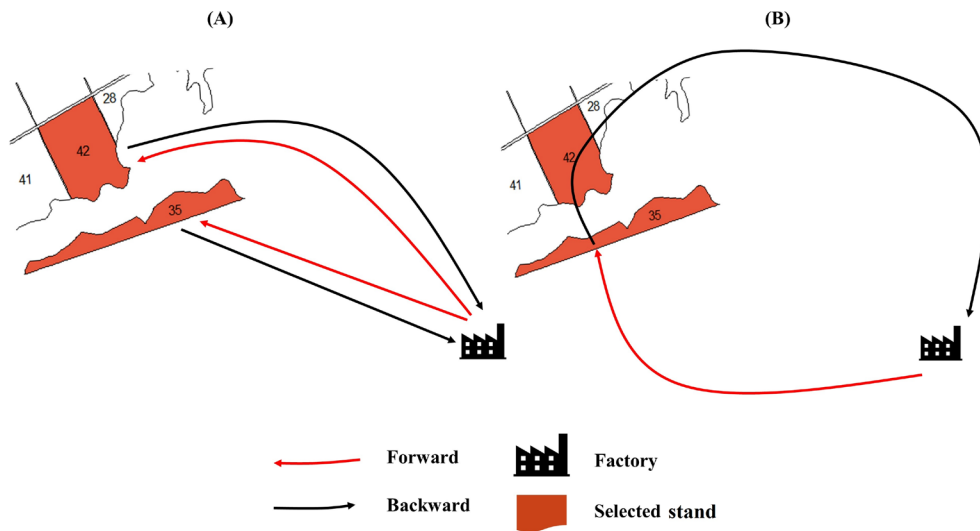


Figure 1. Scheme of simple (a) and multiple (b) displacement of trucks during the task.

Optimization Model (FRoM). The activity to be carried out had the goal of transporting all the timber from 10 stands of *Eucalyptus* sp. The forest inventory had defined the total wood stock around 21,881.82 tons on a project’s landscape of 315.13 ha. The average distance industry-stand is 11.54 km, and the company has available a fleet of 48 trucks. These trucks were classified into two groups, 33 fourteen-wheeler-lorry (29.9 tons/trip) and 15 eighteen-wheeler-lorry (44.7 tons/trip). In addition, the loading activity requires the use of cranes in the field. A total of five (5) machines were available on the stands, all of them having 72.23 tons/hour of productive machine hour. The selected stands derived from the company tactical planning level (Figure 2). The definition of logistics sequencing activity and its integration with the cranes corresponds to the operational planning level, having a planning horizon of 6 days.

Description of the Forest Routing Optimization Model (FRoM)

The developed model operates under the mixed linear integer programming approach applied to the logistics of the forest transportation to

provide a required detail level of the operations for a forest company. The objective function was designed by following minimize the total cost of trucks displacement; minimize trips which the trucks is carrying half-load of its capacity; minimize the number of trucks and minimize overtime cost. The components of the objective function were converted into monetary units (US\$), and then the final objective function, gathering all the described, is to minimize the total transportation cost for the forestry logistic problem.

$$MIN \sum_i^I \sum_j^J \sum_r^R \sum_l^L \sum_d^D c^A \cdot x_{ijrld} + \sum_i^I \sum_j^J \sum_r^R \sum_l^L \sum_d^D c^B \cdot s_{ijrld} + \sum_i^I \sum_d^D c^C \cdot k_{id} + \sum_i^I \sum_d^D c^D \cdot he_{id} \quad (1)$$

Subjected to

$$x_{j0rld} - x_{jOrld} - \sum_i^I x_{jirld} = 0 \quad \forall_j, \forall_r, \forall_l, \forall_d, j \neq 0, j \neq i, i \neq 0 \quad (2)$$

$$x_{jirld} - x_{iOrld} = 0 \quad \forall_i, \forall_j, \forall_r, \forall_l, \forall_d, j \neq i, j \neq 0, i \neq 0 \quad (3)$$

$$Q_i \cdot x_{ijrld} - y_{ijrld} - s_{ijrld} = 0 \quad \forall_i, \forall_j, \forall_r, \forall_l, \forall_d, j \neq i, i \neq 0, j \neq 0 \quad (4)$$

$$\sum_r^R \sum_l^L \sum_d^D y_{ijrld} = V_i \quad \forall_j, \forall_i, j \neq i, i \neq j, i \neq 0 \quad (5)$$

$$\sum_r \left(t^A \cdot x_{0,rld} + t^B \cdot x_{ijrld} + \frac{1}{\eta} \cdot (y_{ijrld} + y_{0,rld}) \right) - H \cdot k_{ld} = he_{ld} \quad \forall_i, \forall_j, \forall_l, \forall_d, j \neq i, j \neq 0, i \neq 0 \quad (6)$$

$$x_{0,jrld} \leq k_{ld} \quad \forall_j, \forall_r, \forall_l, \forall_d, j \neq 0 \quad (7)$$

$$\sum_i g_{icmd} = P_{md} \quad \forall_c, \forall_m, \forall_d, \quad (8)$$

$$\eta \cdot H \cdot \sum_m \sum_c g_{icmd} - \sum_j y_{ijrld} \geq 0 \quad \forall_i, \forall_r, \forall_l, \forall_d, i \neq j \quad (9)$$

$$\sum_m \sum_c g_{icmd} \leq ng_i \quad \forall_i, \forall_d, i \neq 0 \quad (10)$$

$$x_{ijrld}, k_{ld}, g_{icmd} \in \{0,1\} \quad (11)$$

$$s_{ijrld}, y_{ijrld}, he_{ld} \in \{R^+\} \quad (12)$$

The variables x , s , k and he , which x and k are binary, represent the possible routes, the weighted loading slack (in tons of wood), the trucks (in units of vehicle), and the overtime (in hours), respectively. All variables had specific

and sub-indexes, which are trucks l , day d of the planning horizon; i and j representing either stands or factory within each set of routes r which is, for its turn, the combination alternatives of possible routes either between stand-factory and stand-stand. That been stated, the simple and multiple truck displacement were set on each variable which holds these sub-indexes. The constant which converts the amount of run kilometers into monetary unity is c^A expressed in US\$ (US\$1.55/km), c^B represents the constant value paid for the inefficiency on transporting the wood (US\$10.31/tons). This rate of transformation was performed by calculating the efficiency, as performed in Equation 13, for wood transportation over the original data provided by the company. Based on that efficiency value, it was calculated the percentage of the operational cost expressed as US\$/tons of wood. The c^C is the vehicle fixed and variable constant cost (US\$132.32/day), that is, the cost of using a vehicle on a day; and c^D represents the monetary value US\$3.54/hours of the overtime unity (hours).

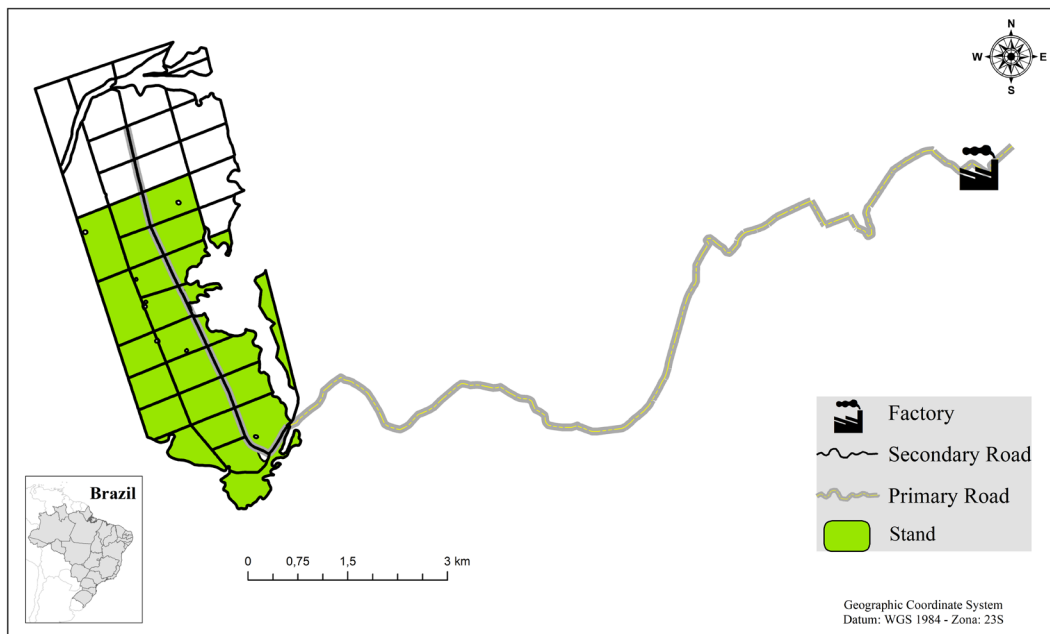


Figure 2. Selected block of stands to transportation task.

The vehicle routing requires a set of restrictions which were in charge of the correct behavior of the model and the industry supply quote (Equations 2-5). The displacement of the truck l over the vertices of the graph (factory or stands) i and j is executed by the constraints represented in the set of equations 2 and 3. The constraint set at Equation 2 forces the trucks to either going from the factory to the stand and return to factory (simple route) or leaving the factory and going to an another stand, starting the multiple routes feature. Additionally, the Equations 3 are responsible for tracking only the multiple movements by bringing the trucks back to the factory and connecting them to the respective route r which creates the movement at Equations 2. The reasoning for that strategy infers the idea that a truck may execute trips between a given stand and the factory due to its lower capacity comparing to the amount of wood offered by the stand. Therefore, the simple movement between a stand and factory occurs several times. Although, it was considered the possibility of departure from a stand towards another stand (multiple route) to complete their full-load capacity with more efficiency. This strategy is essential to reduce the total displacement cost and the amount of half loaded trips.

The constraints set in Equations 4 make the trucks transport wood by applying the variable y , which is the volume carried by a truck exactly addressed to the variable x and considering the load capacity Q of each truck l . The variable s plays a penalty role by accounting for half-load transportation caused by the difference between the expression $Q_l x - y$, which connects the trucks displacement, originally from a binary variable, to the total amount of wood required to be transported, originally as a float variable, considering the industry supply chain conditions. Thus, when the volume of a stand is not multiple

of the number of trips and trucks' carry capacity, at end of the task the trucks would have made more trips to transport the residual lumber. At that moment, the variable s is accounted for penalizing the objective function.

Equations 5 guarantee a complete wood removal from the stands considering the wood volume V available for each stand i and the volume y carried by the truck as an industry supply statement.

The constraint set in Equation 6 has the function to account the total amount of time required to perform the transportation schedule. That total amount of time that crosses the threshold of day work time H , which is equal to 20 hours, is called overtime and it is expressed as he for each day d and truck l . It is applied to the objective function to minimize the operation overtime cost. The aim of these constraints is to sum up the trucks' displacement time, empty and loaded, and the carrying time spent by the cranes. The time is obtained by converting it to hours through the cranes' productive-machine-hour η equals 72.53 tons of wood/hour. The average velocity of the trucks considered for this work on an empty travel was 38km/h. The constants t^A and t^B are the travel time of trucks when empty and loaded, respectively. The displacement of a loaded truck has an increase of time equals 40% regarding the empty truck displacement time. The time for that calculation is obtained by following the basic expression: $T = S/V$, such that T is the time spent during the movement; S is the distance displaced by the truck; and V is the average velocity of the truck. It is important to notice that S varies with the route which each truck executes. The binary variable k controls whether a truck is used on a specific day or not. Therefore, only the trucks that truly work are counting for the time calculation on a specific day d and for each truck l .

The constraint set in Equations 7 has accounted the fleet of vehicles required to execute the transportation. It was assumed that if a truck departs from the factory, which can be mathematically represented when the variable x 's sub-index i is equal to zero, then the variable k for that truck l and day d assumes the value *True*. These constraints are important due the possibility of fleet number reduction along the planning horizon.

The Equations 8 have selected the sequence m on which the cranes c displaces to the stands i on the day d of the planning horizon. The binary variable g is responsible for the crane usage

along the schedule. The matrix P_{md} was previously obtained (Table I) and has all the operational possibilities for the cranes sequencing among the stand. It is important to be aware of that the displacement sequencing of the cranes can change each day according to the behavior of the schedule. Accordingly, several options were provided to the model, making the decision of which produce is the best solution.

The constraint set in the Equation 9 equalizes the volume carried by the trucks (y) within the volume loaded by the cranes ($\eta \cdot H \cdot g$), which g is binary. Thus, the model is able to track the loaded and carried volume. The Equation

Table I. Combination of the crane c of each day from the planning horizon.

Sequencing (m)	Days of the Planning Horizon						Crane Usage (days)
	1	2	3	4	5	6	
1	1 +	1 +	1 +	1 +	1 +	1	6
2	1 +	1 +	1 +	1 +	1 +	0	5
3	0 +	1 +	1 +	1 +	1 +	1	5
4	1 +	1 +	1 +	1 +	0 +	0	4
5	0 +	1 +	1 +	1 +	1 +	0	4
6	0 +	0 +	1 +	1 +	1 +	1	4
7	1 +	1 +	1 +	0 +	0 +	0	3
8	0 +	1 +	1 +	1 +	0 +	0	3
9	0 +	0 +	1 +	1 +	1 +	0	3
10	0 +	0 +	0 +	1 +	1 +	1	3
11	1 +	1 +	0 +	0 +	0 +	0	2
12	0 +	1 +	1 +	0 +	0 +	0	2
13	0 +	0 +	1 +	1 +	0 +	0	2
14	0 +	0 +	0 +	1 +	1 +	0	2
15	0 +	0 +	0 +	0 +	1 +	1	2
16	1 +	0 +	0 +	0 +	0 +	0	1
17	0 +	1 +	0 +	0 +	0 +	0	1
18	0 +	0 +	1 +	0 +	0 +	0	1
19	0 +	0 +	0 +	1 +	0 +	0	1
20	0 +	0 +	0 +	0 +	1 +	0	1
21	0 +	0 +	0 +	0 +	0 +	1	1

10 limits the number of available cranes to the transportation, which was five (5). The Equations 11 and 12 sets up the nature of the decision variables.

Evaluation and Computings

The results have considered the calculation of average efficiency (Equation 13). Efficiency e refers to the real average daily loaded/transported (C_e) wood weight, related to the possible amount of wood that could be transported by the trucks ($C_t = Q \cdot n_v$), in which Q is the carrying capacity of the truck l , and n_v is the number of performed trips. The calculation of the crane's efficiency is similar, where C_t for cranes is $C_t = \eta \cdot H$, where η is the productive machine hour, in tons per hour – tons/h, of the crane c and H is the time in which the transport operations was executed.

$$e = \frac{C_e}{C_t} \times 100 \quad (13)$$

The model was developed in Lingo software version 17.0.60, using a Desktop/Intel® Core™ i5-3570 (3.4GHz) computer. Due to the reliable representation of a forest company, the processing time of one hour was adopted.

RESULTS

The designed FRoM presented 4,195,853 decision variables, of which 257,008 were integer variables, and a total of 2,595,331 constraints, not obtaining a globally optimal solution until the end of processing. The first feasible solution was obtained at 4 minutes and from 31 minutes remained constant until one hour when the processing was interrupted. From the obtained solution, the final cost was US\$53.029,85 (Table II).

During the task, 2,338.24 tons of wood represented the inefficiency regarding the load slack of the trucks, i.e., 89.32% of full load

efficiency. These points of inefficiency were identified in only 17 trips, representing 3.28% of total trips along the planning horizon. The model only applied the Eighteen-wheeler lorry, vehicles with higher capacity, generating a reduction of 73.3% in the number of trucks usually available for the activity. The number of trips per vehicle was higher on the beginning and the end of the planning horizon (Figure 3b). The FRoM has planned the transportation without overtime.

The transported amount of wood and the distance traveled varied throughout the execution of the operation which has impacted the transportation efficiency (Figure 3a and 3c). The average distance traveled by the trucks each day was 2,085.4 km, reaching a maximum value equals 2,585.2 km on the last day of the planning horizon. In the trips scheduling was verified that the number of trucks varied per day. On the days 3 and 4 the number of active vehicles had a reduction reaching a minimum of 11 trucks (Figure 3b). The amount of wood carried was continuously increasing after half of the planning horizon until attain its maximum on the last day of the schedule (4,580 tons) (Figure 3a). The wood was displaced efficiently, depleting the entire stock of the selected stands, leaving no lumber in the field. Although, the task's average efficiency e has reduced starting from 98% in the second day to the minimum of 93.7% on the last day (Figure 3c). The model also has provided the amount of wood transported for each vehicle on the evaluated days (Table III). The average transported wood throughout the planning horizon (1,458.8 tons) and daily transported wood (3,646.9 tons) was sufficient to complete the established quota.

All trucks have transported wood applying as much of time as it was available, such that at the end of planning horizon only one truck (number 12), of those 15 which was applied during the transportation, has had the total

Table II. Financial results from each attained goal.

Objective	Target Variable	Unit Value (US\$)	Final Value (US\$)
Displacement Cost (Km)	X_{ijrld}	1.55·km ⁻¹	18,733.63
Half-Load Capacity Cost (Tons of wood)	S_{ijrld}	10.31·tons ⁻¹	24,107.34
Truck Fleet (Number of trucks)	k_{ld}	132.32·truck ⁻¹ day ⁻¹	10.188,88
Overtime (Hours)	he_{ld}	3.54·hour ⁻¹	0

transported volume lower than 1,000 tons (Table III). The fleet displacement average time in the planning horizon outcome was 3.25 hours/truck. During the execution, 250.35 hours were invested in effective transportation, that is, carrying wood to the industry, representing on average 16.05% of the total available time.

The FRoM has encompassed the sequencing cranes schedule integrated with the truck transportation task. It was applied 5 cranes which were available for loading the trucks in the field. The cranes presented average and daily efficiency of approximately 50% or 36.26 tons/hour in wood loading operation. The greater efficiency was observed on the last day of planning horizon reaching 63.15% or 43.52 tons/hour. On the other hand, it was observed the minimum of efficiency on the third day, reaching 33.84% (Figure 4). The crane number 2 presented higher efficiency e equals 60.82% in the loading wood task, and the crane 4 obtained the lower performance in the same metric (45.44%). The total available time for loading/unloading was 600 hours, considering the five cranes. The model presented as output a use of time equal to 50.28% or 301.7 hours.

DISCUSSION

This paper has shown the complexity of forestry logistics and has proved that it is a case of VRP and can be solved applying the Forest Rout Optimization Model developed and explicitly described. As a case of VRP, the forestry approach could not have been solved applying a mathematical model, as was stated by Lenstra & Rinnooy Kan (1981) and Pierre & Zakaria (2017) regarding the classical VRP. The application of metaheuristics, as applied in Chand et al. (2010), Lau et al. (2010), Chand & Mohanty (2013), Puljic' & Manger (2013), Vaira & Kurasova (2013), Wang et al. (2016), Abdallah et al. (2017), Pierre & Zakaria (2017) could be an option for reduced processing time and may obtain a good response.

The vehicle routing problem is widely used in situations that apply logistics mainly, such as agriculture (Oksanen & Visala 2009, Florentino et al. 2013, Santoro et al. 2017) and industry (Ferreira et al. 2017, Soleimani et al. 2018). However, in forestry companies this problem presents a peculiarity with respect to the classic feature. The forestry routing problem should not be generalized as a multiple traveling salesmen (TSP) like it is regularly assumed to be in literature, and as the creators of the model Dantzig and Ramser stated in 1959.

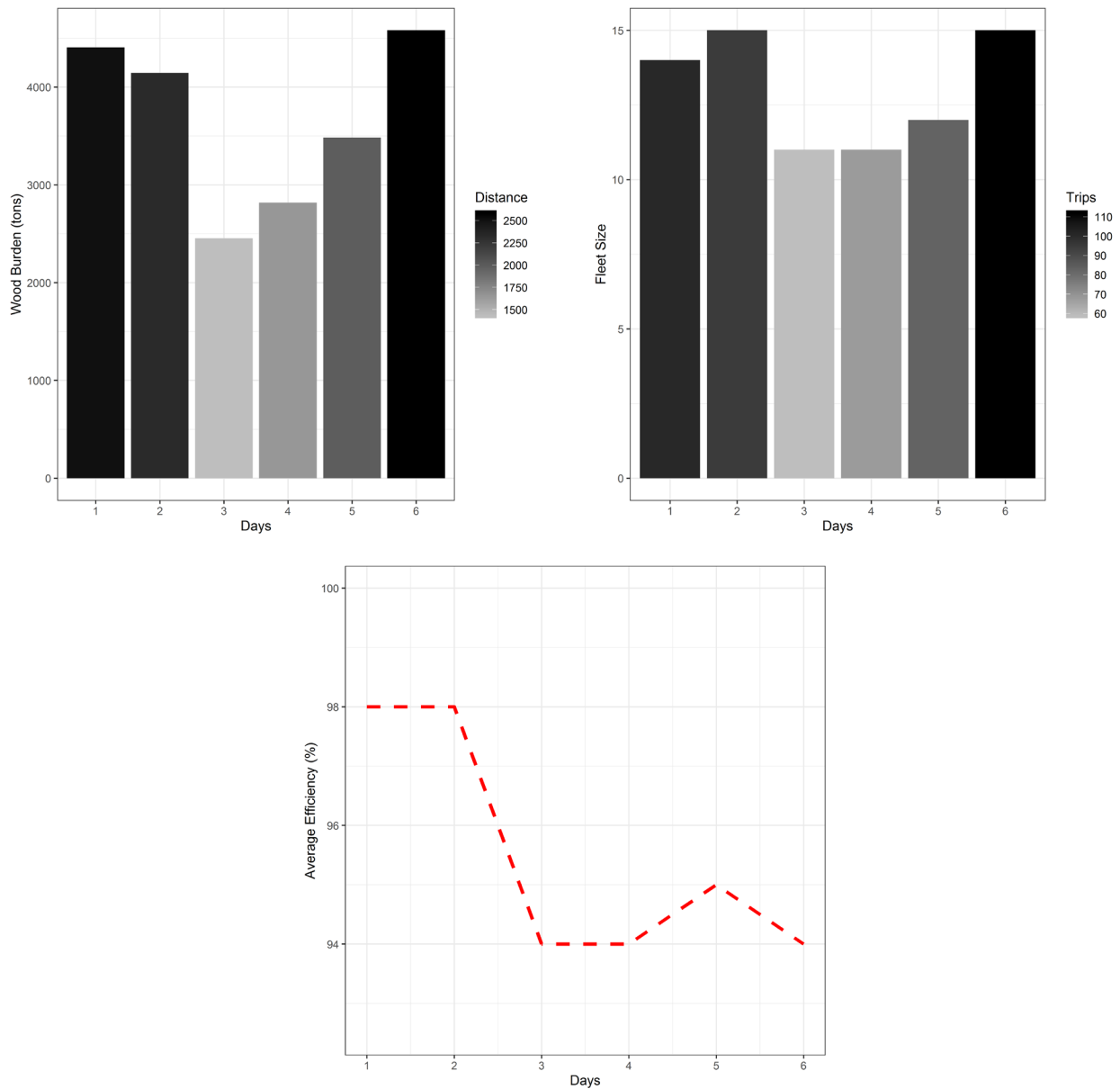


Figure 3. Mathematical model outcome information, where (a) travelled distance, kilometer, (dashed line) and load wood weight, tons, (area under the line); (b) fleet size (dashed line) and number of trips (area under the line); (c) Average efficiency e of transportation by the trucks.

This fact is due to the flow of wood following a straightforward path at the beginning of the activity when it travels from the industry to the stand and comes back to industry right away (simple path). This behavior repeats several times before the trucks start to travel among themselves departing from industry toward a stand, collecting the wood of it and moving

towards another stand right before coming back to industry do unload the wood (multiple path).

The FRoM has returned a final cost of US\$53,029.85 with effective transportation cost equals US\$28,922.52, considering only the cost of the displacement equal to US\$18,733.63, and the fixed cost of using trucks equal to US\$10,188,88 (Table II). The multiple path and simple path

Table III. Lumber weight (ton) transported per truck during the horizon plan.

Truck	Days						Total (tons)
	1	2	3	4	5	6	
1	355.8	178.8	268.2	312.9	223.5	357.6	1,696.8
2	268.2	223.5	0	0	134.1	447	1,072.8
3	311.9	223.5	178.8	358.7	357.6	223.5	1,654.1
4	311.1	268.2	312.9	357.6	0	134.1	1,383.9
5	312.9	357.6	144.7	491.7	134.1	402.3	1,843.3
6	446.1	268.2	0	0	357.6	134.1	1,205.9
7	312.9	268.2	268.2	134.1	402.3	447	1,832.7
8	355.8	312.9	178.8	134.1	0	134.1	1,115.8
9	0	312.9	0	89.4	312.9	357.6	1,072.8
10	267.3	491.7	447	0	312.9	357.6	1,876.5
11	357.6	223.5	89.4	312.9	353.7	400.3	1,737.3
12	306.5	268.2	0	0	0	357.6	932.3
13	401.4	268.2	340.5	357.6	134.1	357.6	1,859.4
14	89.4	121.1	44.7	268.2	357.6	335.6	1,216.6
15	308.9	357.6	178.8	0	402.3	134.1	1,381.7
Total	4,405.7	4,144.1	2,452.0	2,817.2	3,482.7	4,580.0	21,881.8

strategies have worked successfully reducing the number of trips which the trucks would have done if only the simple path strategy was applied. The FROm has shown a dynamic behavior similar to specialist knowledge decision-making process.

The reduction of the truck fleet has provided savings of 73.3% impacting directly to final cost. This strategy has provided saving of investments from the order of 49.12% compared to the original data (with 48 trucks). The total cost of using the 48 trucks in the planning horizon is US\$56.842,71. This margin of savings is higher than which was found by Epstein et al. (1999) and Silva (2015) which stated reductions in transportation costs of 10% to 22% applying the fleet reduction

strategy, which demonstrates the importance of this approach for reduction of cost, traffic, and queues in forestry and agriculture logistics.

The main advantage of the FROm is to apply these two approaches in one single model to be solved by the optimization software. The exhaustive search algorithm considers all combinations within the pool of feasible solutions, which means that applying these two approaches together, one can obtain a solution with integrated analysis. The gain in efficiency of wood transportation was 89.32% by applying the multiple path strategy and there was no need for additional time, elimination the overtime cost. The overtime was eliminated even with the number of trips increasing throughout the

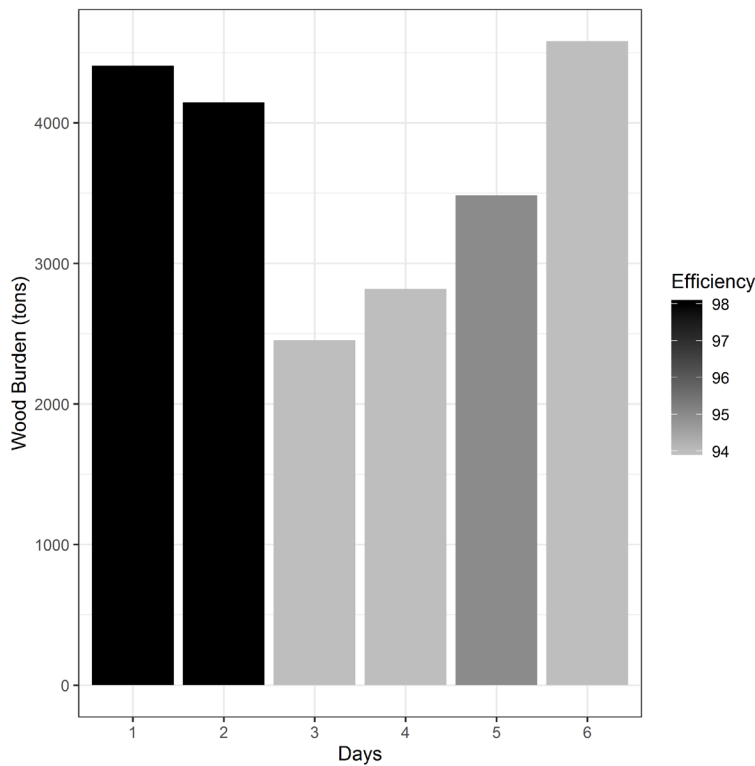


Figure 4. Daily evaluation in the cranes loading/unloading wood task (area under the line) and the cranes efficiency (dashed line).

planning horizon due to the reduction of the fleet size in the middle of the planning horizon. These outcomes besides to reduce the total cost of the operation and provide details for contracts management, also generates the expectation of non-exposure of the worker to a greater risk of accidents (Kalupová & Hlavoň 2016, Reyna et al. 2016).

The weight of wood transportation reduced (Figure 4) due to the withdraw of the burden of smaller stands at the middle of the planning horizon, accordingly, reducing the number of applied trucks. Finally, at the end of the planning horizon, more trucks were sent to obey the wood supply constraint of withdrawing all wood from the stands within 6 days. At that point, the simple and multiple routes were working simultaneously on different stands and trucks, until ending up the burden of the last stands. Nevertheless, the average efficiency e for the trucks was affected reaching its minimum value

of 93.7%. This happened because the model had time to spend and trucks to apply on the transport, then it just released resources to complete the task.

Dynamically, a company will always seek to reduce costs by evaluating the efficiency ratios of machines and equipment. The renewal of technologies is another aspect that acts in this direction. However, the assessment of permanent fleet reduction brings direct benefits to management, which translates into annual costs related to budget targets. Thus, decision-making systems assist in the strategic planning whether in the feasibility analysis of the outsourcing of transportation (Silva 2012) or in the definition of periodic management goals, for instance. The simple and multiple strategies can be applied to assist setting the preventive and predictive trucks maintenance schedule through the predefined costs and routes for each company's vehicle (Figure 5).

The total used time for transportation was 250.35 hours representing, on average, only 16.05% of the total available for transportation (1,560 hours). A hypothesis to fit these situations would be to add the cost of the crane's displacement on the field and the addition of makespan constraints with the purpose of reducing the execution time of the activity, consequently, reducing the likely idleness of the cranes on field. The cranes' movement is another advance in the FRoM approach compared to the main models found in the literature. This increases the model complexity and provides advantages over the used systems which commonly apply the isolated classical transportation problem. The sequencing cranes on the field proved to be effective and necessary for loading/transportation wood providing security on decision-making process. However, the cranes had an average efficiency of 50% which is the precedent for evaluating idleness

on field. The number of days and trucks applied to the problem may have caused this idleness, although the model does not reflect the exact reality of the cranes since the cost/time of its displacement on the field was not contemplated. However, with the addition of this feature and optimizing the crane number, its yield tends to increase.

Thus, minimizing the cost of transportation is directly equivalent to the reduction of inefficient use of vehicles which reduces the emission of CFC gases, traffic accidents, dust and noise risks, reducing the negative impact on the environment as well (Epstein et al. 2007). The benefits are global and positive acting directly as promoters of certification processes (ISO 9.001, ISO 14.001, FSC and OHSAS 18.001). Likewise, an important contribution is the planning of the scheduling/sequencing of activities considering an expressive level of detail. This information, when integrated with

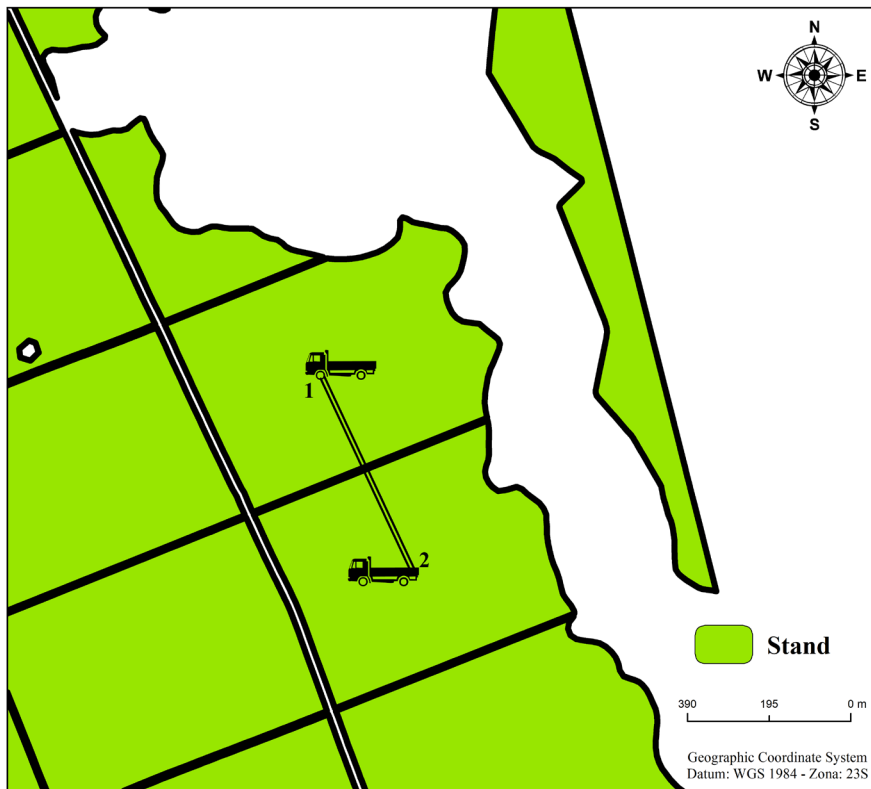


Figure 5. Scheme of double rout applied to wood transportation which the truck leaves the stand 1 and comes to stand 2 before return to factory.

GIS environments (Vopenka et al. 2015) should deeply assist in decision-making process.

An integrated management system covering the whole process emerges as a fundamental tool for the future of forestry operation planning (Souza & Alves 2018). Moving further on the multidisciplinary approach of this subject and associating with new approaches, such as the use of drones, telemetry and GPS integrated into vehicles. The response generated by the FRoM can be incorporated and used in the real-time monitoring vehicle's position/displacement. This allows for the multiple management of several integrated processes, such as periodic factory timber supplies, budget control, detailed costs, vehicle predictive and preventive maintenance, carbon emission, and detailed income control, and increasing of worker's safety. The results obtained, if applied in the supply of wood for industries, can strengthen the economy of the forest sector making it more competitive within Brazilian agribusiness, since there are disputes over land/inputs between companies and product segments.

CONCLUSIONS

This study explored the complexity of the vehicle routing problem under the view of forest logistic system and present the Forest Routing Optimization Model (FRoM) to solve it in a real-case study. The FRoM considered two model reasoning into one feature, the single and multiple route strategies, regarding truck displacement and introduced the cranes modeling to the forest logistic problem. The FRoM provided reduction in the total cost of transportation by reducing the truck fleet, eliminating overtime, and increasing the efficiency of the transportation. In addition, it can help to identify gaps in the operation

proceedings previously, such as idleness of cranes. Therefore, it can be used as a tool for forest logistic planning.

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