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An exact mathematical formulation for the optimal log transportation

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ABSTRACT

In this work, a Mixed-Integer Linear Programming (MILP) model for daily routing of trucks in forest industry is presented. The aim is to generate truck routes at minimum cost, while logs supply is guaranteed. Models usually found in the literature assume that the trips that must be made are known in advance or are generated in a previous stage. Unlike those approaches, in this work the configuration of each trip is generated along with the routing decisions. An exact formulation is developed; neither decomposition algorithm nor heuristics are used. The proposed model is evaluated on several cases, showing in all of them that the proposed approach efficiently solves the addressed problem in a short computational time.

1. Introduction

In forest industry, log transportation represents one of the major impacts on the overall costs. Then, reducing these costs represents a significant saving for companies in the sector. Forest companies have to take several decisions related to the distribution of logs from the harvest areas to the different industries that require them. Therefore, making transportation operations more efficient through an adequate planning represents a task of major interest.

Transportation planning ranges from strategic to operational decisions. At strategic level, decisions are mainly related to road investments, facilities locations and fleet management (Carlsson and Rönnqvist, 2005; Forsberg et al., 2005; Olsson, 2005; Olsson and Lohmander, 2005). At tactical level, decisions are associated to product allocation (Carlgren et al., 2006; Carlsson et al., 2014; Troncoso and Garrido, 2005), while at operational level vehicle routing and scheduling are typical decisions.

Vehicle routing in log transportation is different from traditional Vehicle Routing Problem (VRP) found in the literature. Extensive state-of-the-art works on VRP can be found in Toth and Vigo (2014) and Laporte (2009). Moreover, the log transportation problem is classified as a variation of the Pick-up and Delivery Problem (PDP). Parragh et al. (2008a, 2008b) present detailed definitions and approaches of general PDPs. A number of attributes that distinguish PDP in log transportation from a more general PDP is presented by Audy et al. (2012), where a review of the planning methods regarding the VRP in this industry is also presented.

Borges et al. (2014) define the PDP in log transportation as a set of vehicle routes that must be generated in order to satisfy a set of demand points according to a given objective and subject to a set of constraints. A route usually starts and ends at the vehicle home base and must satisfy different time constraints such as working hours availability of the vehicle (e.g. to disallow working at night), length of driver work shift, time windows at supply/demand points, etc. Also, the supply and demand sites can be visited more than once (logs availability usually exceeds one truckload as well as facility requirements).

To carry out the transportation, a fleet of vehicles is available, which may consist of the same or different vehicle types, each with an unique set of transportation-relevant characteristics (e.g. capacity, types of raw material allowed to haul, fuel consumption, set of sites not allowed or impossible to visit, etc.). The vehicles are spread throughout a set of sites or based in only one location. Therefore, the log transportation problem involves many complex decisions, which includes large number of vehicles, supply and demand nodes, different types of raw material, several starting routing points, and legal and political aspects, among others, making the resolution process very complex. Thus, developing a tool capable of treating and solving this problem efficiently and in a short computational time, is a practical and relevant issue for the industry.

Due to the complexity of this type of problems and the difficulty for obtaining optimal solution in reasonable computing time, many heuristic based approaches were proposed in the literature, as it is described in the following paragraphs.

Palmgren et al. (2003) solve a daily problem through a hierarchical solution approach, which first generates feasible routes with a heuristic algorithm. After solving the LP relaxation of that problem, an integer

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Nomenclature

Sets

C	set of available trucks c
C_p	set of trucks c that belongs to the regional base p
F	set of harvest areas f
I	set of plants i
I_m	set of plants i that requires raw material m
M	types of raw material m
P	regional bases p for trucks
V	set of possible trips v to be made by trucks

Indices

c	trucks, $c = c_1, c_2, \ldots, c_{max}$
f	harvest areas, $f = f_1, f_2, \ldots, f_{max}$
i	plants, $i = i_1, i_2, \ldots, i_{max}$
m	raw material types, $m = m_1, m_2, \ldots, m_{max}$
p	regional bases, $p = p_1, p_2, \ldots, p_{max}$
v	trips, $v = v_1, v_2, \ldots, v_{max}$

Parameters

$CL_{f,i}$	cost (in \$ per traveled kilometer) between harvest area f and plant i
$CUa_{f,i}$	cost (in \$ per traveled kilometer) between harvest area f and plant i
$CUb_{p,f}$	cost (in \$ per traveled kilometer) between regional base p and harvest area f (without load)
$CUc_{p,i}$	cost (in \$ per traveled kilometer) between regional base p and plant i (without load)
$Ctruck_c$	fixed cost (in \$ per truck used) associated with each truck c
$DEM_{i,m}$	demand of raw material m required by plant i, in full-truckloads
$DFI_{f,i}$	distance (in kilometers) between harvest area f and plant i
$DPF_{p,f}$	distance (in kilometers) between regional base p and harvest area f
$DPI_{p,i}$	distance (in kilometers) between regional base p and plant i
$MaxT$	route time limit
$OF_{f,m}$	availability of raw material m at harvest area f, in full-truckloads
$VLT_{f,i}$	average speed (in kilometers per hour) for the loaded trip that links harvest area f and plant i
$VUTa_{p,f}$	average speed (in kilometers per hour) for the unloaded trip that links regional base p and harvest area f
$VUTb_{f,i}$	average speed (in kilometers per hour) for the unloaded trip that links harvest area f and plant i
$VUTc_{p,i}$	average speed (in kilometers per hour) for the unloaded trip that links regional base p and plant i

Binary variables

$x^D_{c,p,f,v}$	takes value 1 if truck c begins the routing in its associated regional base p to visit the first harvest area f, 0 otherwise
$x^L_{c,f,i,v}$	takes value 1 if truck c makes a loaded trip v from harvest area f to plant i, 0 otherwise
$x^R_{c,i,p,v}$	takes value 1 if truck c makes a return trip v from the last visited plant i to its associated regional base p, 0 otherwise
$x^U_{c,i,f,v}$	takes value 1 if truck c makes an unloaded trip v from plant i to harvest area f to realize a new loaded trip, 0 otherwise
y_c	takes value 1 if the truck c is used, 0 otherwise

Continuous variables

$TCOST$	total transportation costs
$TIME_c$	total working time (in hours) of truck c

solution is obtained by a branch and price method. In a similar fashion, in Palmgren et al. (2004) the same problem is solved by applying a k-shortest path algorithm in the branch and price method. Rey et al. (2009) propose a Column Generation (CG) method for solving a similar formulation to the one proposed by Palmgren et al. (2003), but in this case the linear relaxation of the model is solved via dynamic column generation. A CG method to tackle a multi-period configuration is proposed by Rix et al. (2011). Later, Rix et al. (2014) generalize the previous model to take into account loader synchronization.

In El Hachemi et al. (2011), the authors present a decomposition approach based on Constraint Programming (CP) and Integer Programming (IP). In their approach, transportation tasks are pre-defined, so the objective is to minimize the total cost of non-productivity activities such as waiting time of trucks and forest loaders and distances traveled by empty trucks.

A hierarchical approach to solve the weekly problem is proposed in El Hachemi et al. (2013). In the first phase a MILP model is used to determine the destinations of full truckloads from forest areas to wood mills. In the second phase, two different methods to route and schedule the daily transportation of logs are used: a Constraint-Based Local Search approach (CBLS), and a hybrid approach involving a CP based model and a CBLS model. The same problem is solved in El Hachemi et al. (2014) through a similar approach for the first stage, and in a second stage a flow-based model with a specialized branching strategy is used to routing and scheduling trucks at minimum cost.

Gronalt and Hirsch (2007) propose a Tabu Search (TS) method to generate daily log truck route schedules for pre-defined transportation requests. The objective is to minimize the overall duration of empty truck movements considering weight constraints on the road network, multi-depots and time windows. A Simulated Annealing (SA) algorithm considering capacity and time windows constraints is developed in Haridass et al. (2014). In Flisberg et al. (2009), the authors also propose a TS approach for the operational routing problem to decide the daily routes of logging trucks in forestry. In the first phase, transportation nodes are created using a heuristic or a mixed integer programming model (a way to decompose the problem into a standard VRP with time windows). In the second phase, VRP with time windows is solved via TS.

A recent description of the current status and challenges in forest planning is provided by Rönnqvist et al. (2015). The authors state that even if there are many approaches and methods developed for the forest routing problem, there is no exact formulation proposed in the literature and used in practice for industrial instances. Also, Audy et al. (2011) highlight that there is no article, at that moment, that jointly considers those decisions (allocation, routing and scheduling).

In order to overcome this drawback, in this work a MILP model that simultaneously generates routes, assigns trucks to routes, and sequences vehicle trips is presented. Neither decomposition techniques nor heuristic algorithms are used but an exact formulation. Decisions that are generally considered in different stages, that is, product allocation and truck routing decisions, are integrated. Approaches found in the literature assume that trips are known in advance (or are generated in a previous stage). Unlike these approaches, in this work the configuration of each trip is jointly generated with the routing decisions.

The focus of this article is on operational planning decisions, specifically in how to determine the set of routes to be performed by a fleet of trucks to deliver logs from harvest areas to production plants, at minimum cost. The MILP model incorporates decisions of product allocation to facilities and routing of the truck fleet. The novelty of the proposed approach is the way that routes are generated, which allows to obtain optimal solution in reduced computing time. The capabilities of this proposal are shown through some examples developed for the Argentine forest industry.

In the following section, the problem to be modeled is described. In Sections 3 and 4 the proposed mathematical model and the application examples with the obtained results are presented, respectively. Finally, in the last section, conclusions are exposed.

2. Problem description

Let F be the set of harvest areas f, $f \in F$. At each harvest area f, there is an available amount $OF_{f,m}$ of raw material m, $m \in M$, (expressed in number of full-truckloads) used to supply a set of plants i, $i \in I$. Raw materials are classified taking into account their destination: to be used in sawmills, paper mills, etc. Each plant i demands a certain amount $DEM_{i,m}$ of a type of raw material m (also expressed in full-truckloads).

A set of trucks c, $c \in C$, is available. Each truck begins and finishes its route in a regional base p, $p \in P$. In addition, each truck c can make a limited number of trips, and transports only one type of raw material m at a time.

Each route is composed by a series of trips v, $v \in V$, where a trip v is a sequence of different movements (Fig. 1). Many times the number of trips included in a route is limited by certain regulations. For example, a route can include at most three trips or cycles, beyond which the truck has time to make more trips. Four types of trips are defined:

a) If the route is composed by only one trip v, it has a departure movement (unloaded) from the regional base p to a harvest area f, a loaded movement from the harvest area f to plant i, and a return movement (unloaded) from that plant i to the regional base p.
b) If the route has more than one trip, its first trip is composed by a departure movement (unloaded) from the regional base p to a harvest area f, a loaded movement from that harvest area f to plant i, and an unloaded movement from that plant i to a harvest area f' (not necessarily equal to f) to make a new loaded trip.
c) If the trip is neither the last one nor the first one of the route, then it is composed by a loaded movement from harvest area f to a plant i and an unloaded movement from that plant i to a harvest area f' (not necessarily equal to f) to make a new loaded trip.
d) If the trip is the last one in the truck route but is not the first one, then it is composed by a loaded movement from harvest area f to plant i and a return movement (unloaded) from that plant i to the regional base p.

As can be seen, the first two types of trips are made up by three movements, two unloaded and another loaded, meanwhile the two remaining are conformed by two movements, one unloaded and another loaded.

Therefore, according to the above trip definition, the proposed approach assembles the routes through trip compositions which are simultaneously assigned to the truck in the overall model. Taking into account the four types previously defined, all possible routes can be made up using them.

Fig. 2 shows two routes composed by two and three trips, respectively. All the types of trips include a truck movement loaded and another one unloaded to and from a plant. Besides, all the routes must contain a trip from a regional base and another one (or the same one) to return to that regional base. Once the trips have been assigned, the variables that define the movements are effectively defined through appropriate constraints that will be presented in the next section.

This form of route construction as a succession of trips and, in turn, these trips as a concatenation of movements, allows representing the full problem with a reduced number of binary variables, unlike the approaches proposed in the literature.

3. Mathematical model

In this section, the mathematical modeling is described.

3.1. Objective function

The problem objective is to minimize total transportation costs, $TCOST$. These costs are divided into two parts: a fixed cost per truck use and a variable cost that depends on the traveled kilometers with and without load and road characteristics (Eq. (1)):

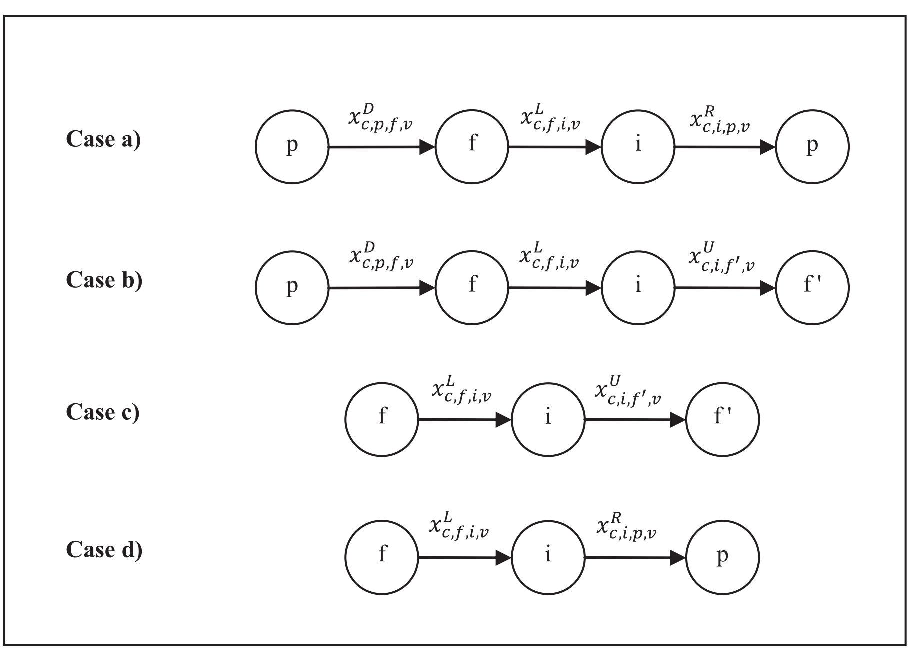

Fig. 1. Trip composition and involved variables.

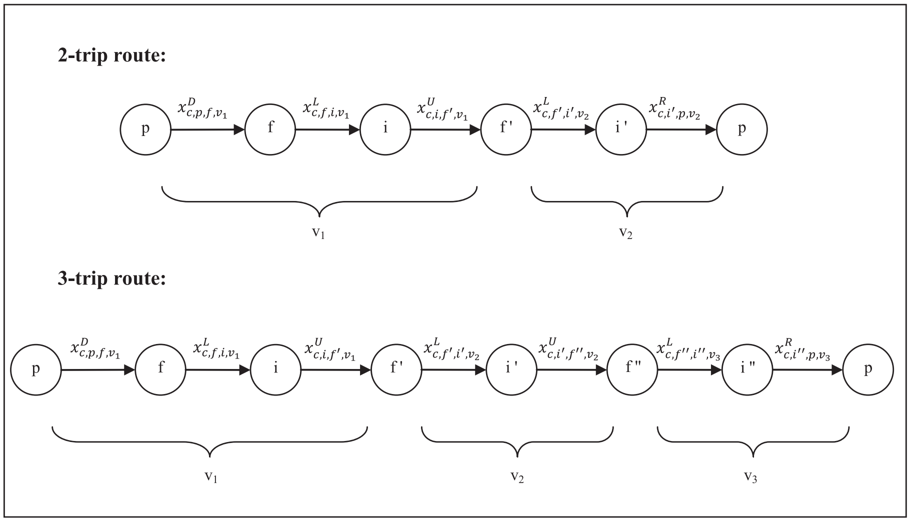

Fig. 2. Example of routes composed by two and three trips.

$$min\ TCOST = \sum_{c\in C}\sum_{f\in F}\sum_{i\in I}\sum_{v\in V}(CL_{f,i}\ DFI_{f,i}\ x^{L}_{c,f,i,v}) + \sum_{c\in C}\sum_{f\in F}\sum_{i\in I}\sum_{v\in V}(CUa_{f,i}\ DFI_{f,i}\ x^{U}_{c,i,f,v}) + \sum_{p\in P}\sum_{c\in C_p}\sum_{f\in F}\sum_{v\in V}(CUb_{p,f}\ DPF_{p,f}\ x^{D}_{c,p,f,v}) + \sum_{p\in P}\sum_{c\in C_p}\sum_{i\in I}\sum_{v\in V}(CUc_{p,i}\ DPI_{p,i}\ x^{R}_{c,i,p,v}) + \sum_{c\in C}(Ctruck_c\ y_c) \quad (1)$$

where C_p is the subset of trucks c settled at regional base p.

The first four terms of the objective function correspond to the costs for the different movements that can make up a trip. This definition not only considers distances between nodes but also the route characteristics (type of pavement, geography, etc.) through appropriate parameters. The first term of Eq. (1) represents the costs of making loaded movements between harvest area f and plant i. The completion of this loaded movement is represented by the binary variable $x^{L}_{c,f,i,v}$ that takes value 1 if truck c goes from harvest area f to plant i in trip v. Parameters $DFI_{f,i}$ and $CL_{f,i}$ correspond to the distance (in kilometers) between both sites and the cost of travelling that path (in $ per traveled kilometer), respectively.

The second term indicates the costs of making unloaded movements from plant i to harvest area f. The binary variable $x^{U}_{c,i,f,v}$ takes value 1 if such movement is realized. $CUa_{f,i}$ represents the cost of travelling the path between i and f (in $ per traveled kilometer).

The third term states the costs of making departure movements from the regional base p to harvest area f. $x^{D}_{c,p,f,v}$ is the binary variable that represents the realization of the movement that links the regional base p with the first visited harvest area f. Parameters $DPF_{p,f}$ and $CUb_{p,f}$ represent the distance between regional base p and harvest area f (in kilometers) and the cost of travelling that road (in $ per traveled kilometer), respectively.

The fourth term calculates the costs of making return movements from plant i to the regional base p. The binary variable $x^{R}_{c,i,p,v}$ takes value 1 if such movement is carried out. Parameters $DPI_{p,i}$ and $CUc_{p,i}$ represent the distance between plant i and the regional base p (in kilometers) and the cost of travelling that path (in $ per traveled kilometer), respectively.

The last term represents the fixed costs of trucks use. The binary variable y_c represents the utilization of truck c, independently of the traveled distance, and the cost associated with each truck is given by $Ctruck_c$.

3.2. Constraints

The available raw materials at each harvest area as well demand of each plant are expressed in term of number of full-trucks. Therefore, the total loaded movements of each type of raw material m sent from harvest area f to any plants cannot exceed the availability of that type of raw material in that area, denoted by $OF_{f,m}$:

$$\sum_{c\in C}\sum_{v\in V}\sum_{i\in I_m} x^{L}_{c,f,i,v} \le OF_{f,m} \quad \forall f\in F,\ m\in M \quad (2)$$

where I_m is the set of plants i that require raw material m.

The loaded movements of certain type of raw material m that arrive to plant i must fulfill the plant demand $DEM_{i,m}$:

$$\sum_{c\in C}\sum_{v\in V}\sum_{f\in F} x^{L}_{c,f,i,v} = DEM_{i,m} \quad \forall m\in M,\ i\in I_m \quad (3)$$

As was previously defined, this formulation configures the route used by each truck. Once a trip is included in a route, several constraints are generated in order to assure the appropriate movements are included in each trip.

If truck c is not assigned, no movement is done. This condition is represented by Eqs. (4) and (5):

$$\sum_{f\in F}\sum_{i\in I} x^{L}_{c,f,i,v} \le y_c \quad \forall c\in C,\ v\in V \quad (4)$$

$$\sum_{f\in F}\sum_{i\in I} x^{U}_{c,i,f,v} \le y_c \quad \forall c\in C,\ v\in V \quad (5)$$

Eq. (6) states that, if the truck c is assigned to its first trip (i.e. $v = v_1$) from harvest area f to any plant i then, it must necessarily leave from its regional base p to that harvest area f:

$$\sum_{i\in I} x^{L}_{c,f,i,v_1} = x^{D}_{c,p,f,v_1} \quad \forall p\in P,\ c\in C_p,\ f\in F \quad (6)$$

Also, if truck c is used, then it must make an unloaded trip from its regional base p to some harvest area f:

$$\sum_{f\in F} x^{D}_{c,p,f,v_1} = y_c \quad \forall p\in P,\ c\in C_p \quad (7)$$

In the same way, if truck c is used, it has to return to its regional base p from the last visited plant i:

$$\sum_{v\in V}\sum_{i\in I} x^{R}_{c,i,p,v} = y_c \quad \forall\, p \in P,\ c \in C_p \tag{8}$$

If truck c is used, then it must realize at least one loaded movement from harvest area f to plant i (Eq. (9)):

$$y_c \le \sum_{v\in V}\sum_{f\in F}\sum_{i\in I} x^{L}_{c,f,i,v} \quad \forall\, c \in C \tag{9}$$

In order to avoid alternative solutions, trips are generated in ascending order for each truck c, i.e. if the trip v is not performed, the trip $(v+1)$ neither:

$$x^{L}_{c,f,i,v+1} \le \sum_{f'\in F}\sum_{i'\in I} x^{L}_{c,f',i',v} \quad \forall\, c \in C, v \in V, f \in F, i \in I \tag{10}$$

Constraint (11) states that if truck c during trip v does not make a loaded movement from any harvest area f to some plant i, it neither makes the associated unloaded movement:

$$\sum_{f\in F} x^{L}_{c,f,i,v} \ge \sum_{f\in F} x^{U}_{c,i,f,v} \quad \forall\, c \in C,\ v \in V,\ i \in I \tag{11}$$

When the route includes more than one trip, Eq. (12) forces the completion of a loaded movement from the harvest area f to a plant i' in the last trip only if a previous unloaded movement arrives at the harvest area f from any plant i:

$$\sum_{i\in I} x^{U}_{c,i,f,v-1} = \sum_{i\in I} x^{L}_{c,f,i,v} \quad \forall\, c \in C,\ v > v_1,\ f \in F \tag{12}$$

Thus, if different trips compose a route, they are appropriately linked. After finishing a loaded movement, truck c can either return to the regional base p or go to a new harvest area f to perform the following trip:

$$\sum_{f\in F} x^{U}_{c,i,f,v} + x^{R}_{c,i,p,v} = \sum_{f\in F} x^{L}_{c,f,i,v} \quad \forall\, p \in P, c \in C_p, v \in V, i \in I \tag{13}$$

Constraint (14) defines the total working time of truck c ($TIME_c$), calculated through the spent time for realizing the different movements for each trip v:

$$\begin{aligned} TIME_c = & \\ & \sum_{p\in P}\sum_{v\in V}\sum_{f\in F} \frac{DPF_{p,f}}{VUTa_{p,f}} x^{D}_{c,p,f,v} + \\ & \sum_{v\in V}\sum_{f\in F}\sum_{i\in I} \frac{DFI_{f,i}}{VLT_{f,i}} x^{L}_{c,f,i,v} + \\ & \sum_{v\in V}\sum_{f\in F}\sum_{i\in I} \frac{DFI_{f,i}}{VUTb_{f,i}} x^{U}_{c,i,f,v} + \\ & \sum_{p\in P}\sum_{v\in V}\sum_{i\in I} \frac{DPI_{p,i}}{VUTc_{p,i}} x^{R}_{c,i,p,v} \quad \forall\, c \in C_p \end{aligned} \tag{14}$$

Parameter $VLT_{f,i}$ represents the average speed (in kilometers per hour) for loaded movement at road that links nodes f and i. Parameters $VUTa_{p,f}$, $VUTb_{f,i}$ and $VUTc_{p,i}$ represent the average speed (in kilometers per hour) for unloaded trip between p and f, f and i, and p and i, respectively. These average speeds depend on the specific road.

In addition, each truck c has a limited route time, $MaxT$:

$$TIME_c \le MaxT \quad \forall\, c \in C \tag{15}$$

4. Examples

In this section, two cases based on the Argentine context are presented for analyzing the capabilities and performance of the proposed MILP model. In all the cases, the following parameters are considered: average truck speed with and without load are equal to 55 and 65 km/h, respectively for all roads; costs per traveled kilometer with and without load are assumed equal to 1.2 and 0.8 $/km, respectively, for all roads.

A homogeneous truck fleet is considered in all the studied cases. Therefore in order to avoid alternative solutions and consequently, accelerate the model resolution, Eq. (16) is added. This constraint sorts the use of trucks belonging to the same regional base p which can be made since all trucks are similar.

$$y_c \ge y_{c+1} \quad \forall\, p \in P,\ c \in C_p,\ (c+1) \in C_p \tag{16}$$

The utilization cost per truck is $ 30, each truck can make at most 3 trips, and each truck route cannot exceed 10 hours.

Following, two examples are presented varying the number and locations of regional bases for trucks, harvest areas, raw material types, and plants. Finally, in order to assess the model performance, different scenarios are presented and solved.

All the models are implemented and solved in GAMS (Rosenthal, 2017) 24.7.3 version, using CPLEX 12.6.3 solver in an Intel(R) Core (TM) i7-4790, 3.60 GHz.

4.1. Case A

In order to show the model characteristics, a Supply Chain (SC) composed by 5 sawmills, 5 harvest areas and 1 regional base is considered. There are 300 available trucks for hauling 750 full-truckloads of a unique raw material. Distances between harvest areas and plants, between the regional base and plants, between the regional base and harvest areas, raw material availability, and plants demands are displayed in Table 1.

The model comprises 54,300 binary variables, 301 continuous variables and 86,410 equations. It is solved in 31.14 s with 0% optimality gap, and the objective function value is equal to $ 116,351.20. In this case, 250 trucks are utilized and each one completes three loaded movements in its respective route, i.e. the limit of available trips.

In Table 2 it can be seen that the plants, in the optimum, are supplied by a subset of harvest areas, and in cases such as i_2 and f_4, harvest areas dedicated exclusively to the supply of a single plant.

In this example, it can be seen that the harvest area f_3 supplies a larger number of plants and depletes the available raw material (raw material availability is larger than in the others harvest areas). This would indicate that, if the supply of raw material could be extended, the harvest area f_3 would be the most suitable potential candidate to increase its supply level. In the same way, at raw material sites f_1 and f_2 the total available full-truckloads are distributed, and therefore, it would be beneficial extending the amount of raw material availability there.

4.2. Case B

In this case, adapted from a real instance, the considered SC involves 6 plants, 15 harvest areas and 12 regional bases. There are 400 available trucks for hauling 750 full-truckloads of 3 types of raw material (m_1, m_2, and m_3 for serving sawmills, pulp and paper plants, and

Table 1
Distances (in km) between different nodes, raw material availability and demands (in full-truckloads).

	i_1	i_2	i_3	i_4	i_5	p_1	Raw material availability (full-truckloads)
f_1	120	110	45	42	112	135	143
f_2	42	128	71	134	22	61	130
f_3	98	81	61	92	71	86	241
f_4	136	92	155	194	82	45	98
f_5	76	165	142	206	54	54	188
p_1	92	112	125	177	40		
Demand (full-truckloads)	150	170	150	160	120		

Table 2
Loaded movements generated between harvest area and plants, and remaining raw materials (in full-truckloads).

	i_1	i_2	i_3	i_4	i_5	Remaining raw material
f_1			55	88		
f_2	75				55	
f_3		74	95	72		
f_4		96				2
f_5	75				65	48

heating plants, respectively). Distances between harvest areas and plants, raw material availability and demands are shown in Table 3. Distances between regional bases and plants, and between regional bases and harvest areas are shown in Tables 4 and 5, respectively.

The model in this case involves 241,600 binary variables, 401 continuous variables and 361,240 equations, and the optimal solution is obtained in 243.41 s with 0% optimality gap and with objective function equal to $69,596. From the 400 available trucks, 250 trucks are utilized. In Table 6, for space reasons, only some truck routes are presented so that the characteristics of the solution can be appreciated in detail. For each truck, all the trips it covers and the time required are detailed.

As can be seen in Table 6, truck routes duration are relatively short, and all of them involve three trips, which is the fixed limit. The average route duration is 4.09 hours. Therefore, if more trips per truck are allowed, a smaller number of trucks can be used. Thus, in order to analyze this option, Case B is modified considering a new set of trips, $V^{NEW} = v_1, v_2, \ldots, v_5$. This modification means that 5 trips per truck are allowed.

Now, in the optimal solution only 150 trucks are used, and each one makes 5 trips in its respective route. The average route duration increases to 6.57 hours meanwhile the overall cost decreases by 7.15% with respect to the original Case B. Table 7 shows the model statistics for both cases (Case B with up to 3 and 5 trips, respectively).

Some interesting conclusions from the comparison of Case B versions can be obtained. On the one hand, since the number of used trucks decreases, some regional bases are no longer needed in the resolution with $v_{max} = 5$ (trucks from regional bases p_8, p_{10} and p_{11} are not used). In Table 8, the number of trucks used (unused) per regional base in both solutions is presented.

On the other hand, the amount of traveled kilometers (with load) is practically not affected by the increase of allowed trips per truck. This is due the model generates the same loaded trips as for the original Case B, except that in this case it rearranges them in a smaller number of trucks. Generated loaded movements and the remaining raw materials are shown in Table 9.

Table 4
Distances between regional bases p and plants i, in kilometers for Case B.

	i_1	i_2	i_3	i_4	i_5	i_6
p_1	63	22	90	89	78	108
p_2	10	86	134	73	91	81
p_3	92	20	51	90	63	110
p_4	51	130	163	76	108	71
p_5	71	67	64	32	10	51
p_6	51	81	92	14	36	32
p_7	86	36	41	71	41	91
p_8	28	54	98	57	61	72
p_9	100	100	71	41	28	50
p_{10}	124	128	91	61	57	61
p_{11}	122	120	81	60	50	63
p_{12}	32	50	104	71	73	86

These results indicate that, if it would be possible to incorporate more trucks to the regional bases that use all the available vehicles, or even rearrange them in others regional bases, the solution can be economically more attractive.

4.3. Model performance

In this section, the performance of the presented approach is assessed through diverse study cases. In Table 10, different scenarios are stated, for which the number of available trucks, regional truck bases, harvest areas, raw material types, plants, and demands are varied. Three trips per truck are allowed in all examples. Cases A and B (the original one) previously presented, correspond to scenarios 7 and 20, respectively.

In Table 11 the obtained results are shown. The time limit for solver execution is 300 CPU seconds. Only three scenarios (3, 16 and 19) do not arrive at the optimal solution before the time limit. These cases involve the greater number of available trucks (400 and 500) and the maximum required demands (750 and 1000 full-truckloads). Although the global optimum in these examples is not reached at the fixed limit time, the model finds a solution with a reasonable optimality gap (less than 1%).

5. Conclusions

Transportation planning in forest industry is a critical problem taking into account the high incidence of transport costs in the

Table 3
Distance (km) between harvest areas f and plants i, raw material availability, and demands for Case B.

	i_1	i_2	i_3	i_4	i_5	i_6	Raw material availability (full-truckloads)		
							m_1	m_2	m_3
f_1	71	50	120	114	108	130	22	10	15
f_2	106	40	32	92	60	112	22	14	23
f_3	78	14	60	81	58	100	10	13	35
f_4	92	32	40	81	51	100	15	9	15
f_5	121	73	10	86	50	103	15	7	20
f_6	72	36	54	60	36	80	13	6	19
f_7	41	58	122	92	95	106	10	11	15
f_8	45	50	81	45	41	63	39	13	30
f_9	80	81	67	28	10	45	10	12	20
f_{10}	41	80	99	22	45	36	25	15	25
f_{11}	102	108	81	40	36	45	48	9	25
f_{12}	85	108	95	22	40	22	15	10	15
f_{13}	32	104	135	51	81	51	30	6	50
f_{14}	58	120	136	42	78	32	10	10	20
f_{15}	20	73	108	45	61	57	16	15	23
Demand (type of raw material), in full-truckloads	150 (m_1)	140 (m_2)	65 (m_3)	130 (m_1)	150 (m_3)	115 (m_3)			

Table 5
Distances between regional bases *p* and harvest areas *f*, in kilometers for Case B.

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
p_1	32	61	30	50	91	45	36	45	85	73	113	108	91	110	60
p_2	70	114	85	100	130	81	40	54	90	51	112	95	36	64	30
p_3	70	20	14	14	54	30	76	54	73	82	98	102	112	124	81
p_4	120	150	125	136	156	114	90	86	103	64	114	92	28	40	58
p_5	100	61	54	50	57	32	85	32	14	36	42	41	72	72	51
p_6	100	85	70	73	85	51	78	32	32	10	51	36	45	45	32
p_7	82	22	22	10	40	14	81	42	51	67	76	81	100	108	71
p_8	58	78	50	64	95	45	36	20	63	36	89	78	51	71	20
p_9	136	82	86	76	61	64	121	67	22	60	10	28	92	81	81
p_{10}	164	108	114	103	81	92	148	94	50	82	22	40	110	92	104
p_{11}	158	98	106	94	71	85	143	89	45	81	20	41	110	95	102
p_{12}	45	81	50	67	102	51	22	32	76	50	103	92	60	82	32

Table 6
Truck route description for optimal solution of Case B considering up to 3 trips.

Truck	Trip 1 (v_1)		Trip 2 (v_2)		Trip 3 (v_3)			Route Duration (h)
c_1	p_1-f_1	f_1-i_1	i_1-f_{15}	f_{15}-i_6	i_6-f_{12}	f_{12}-i_2	i_2-p_1	5.77
c_2	p_1-f_1	f_1-i_1	i_1-f_{13}	f_{13}-i_6	i_6-f_{12}	f_{12}-i_2	i_2-p_1	5.84
c_3	p_1-f_1	f_1-i_1	i_1-f_{15}	f_{15}-i_5	i_5-f_9	f9-i2	i_2-p_1	5.17
…	…	…	…	…	…	…	…	…
c_{21}	p_2-f_{13}	f_{13}-i_6	i_6-f_{14}	f_{14}-i_6	i_6-f_{13}	f_{13}-i_1	i_1-p_2	4.08
c_{22}	p_2-f_{13}	f_{13}-i_6	i_6-f_{14}	f_{14}-i_6	i_6-f_{13}	f_{13}-i_1	i_1-p_2	4.08
c_{23}	p_2-f_{13}	f_{13}-i_6	i_6-f_{14}	f_{14}-i_6	i_6-f_{13}	f_{13}-i_1	i_1-p_2	4.08
…	…	…	…	…	…	…	…	…
c_{41}	p_3-f_2	f_2-i_3	i_3-f_5	f_5-i_3	i_3-f_5	f_5-i_2	i_2-p_3	3.01
c_{42}	p_3-f_2	f_2-i_3	i3-f2	f_2-i_3	i_3-f_5	f_5-i_2	i_2-p_3	3.75
c_{43}	p_3-f_2	f_2-i_3	i_3-f_5	f_5-i_3	i_3-f_2	f_2-i_2	i_2-p_3	2.75
…	…	…	…	…	…	…	…	…
c_{161}	p_9-f_{11}	f_{11}-i_4	i_4-f_{10}	f_{10}-i_4	i_4-f_{11}	f_{11}-i_5	i_5-p_9	3.32
c_{162}	p_9-f_{11}	f_{11}-i_4	i_4-f_{10}	f_{10}-i_4	i_4-f_8	f_8-i_5	i_5-p_9	3.49
c_{163}	p_9-f_{11}	f_{11}-i_4	i_4-f_{10}	f_{10}-i_4	i_4-f_8	f_8-i_5	i_5-p_9	3.49
…	…	…	…	…	…	…	…	…
c_{321}	p_{12}-f_1	f_1-i_1	i_1-f_{15}	f_{15}-i_2	i_2-f_3	f_4-i_1	i_1-p_{12}	6.28
c_{322}	p_{12}-f_7	f_7-i_2	i_2-f_1	f_1-i_1	i_1-f_{15}	f_{15}-i_1	i_1-p_{12}	4.62
…	…	…	…	…	…	…	…	…
c_{361}	p_{12}-f_7	f_7-i_2	i_2-f_3	f_3-i_3	i_3-f_2	f_2-i_1	i_1-p_{12}	5.61

Table 7
Results comparison of Case B.

	$v_{max} = 3$	$v_{max} = 5$
Binary variables	241,600	402,400
Continuous variables	401	401
Equations	361,240	600,400
Objective function ($)	69,596	64,621.60
Used trucks	250	150
Traveled kilometers (with load)	34,800	34,792
Total traveled kilometers	60,220	57,756
Average route duration (h)	4.09	6.57
Resolution time (s)	243.41	6233.33

Table 8
Trucks utilization (availability).

Regional base	$v_{max} = 3$	$v_{max} = 5$
p_1	20 (0)	20 (0)
p_2	20 (0)	20 (0)
p_3	20 (0)	20 (0)
p_4	(20)	(20)
p_5	20 (0)	20 (0)
p_6	20 (0)	20 (0)
p_7	20 (0)	5 (15)
p_8	20 (0)	(20)
p_9	40 (0)	40 (0)
p_{10}	(50)	(50)
p_{11}	28 (42)	(70)
p_{12}	42 (38)	5 (75)

Table 9
Loaded movements generated and the remaining raw materials (in full-truck-loads).

	i_1	i_2	i_3	i_4	i_5	i_6	Remaining raw material		
							m_1	m_2	m_3
f_1	22	10							15
f_2		14	23	2			20		
f_3	10	13	7		28				
f_4	15	9	15						
f_5		7	20	15					
f_6	8	6		5	19				
f_7	10	11			10				5
f_8	39	13			30				
f_9		12		10	20				
f_{10}		15		25		25			
f_{11}		4		48	25			5	
f_{12}		10		15		15			
f_{13}	30	1				50		5	
f_{14}				10		20		10	
f_{15}	16	15			18	5			

Table 10
Model characteristics for each studied scenario.

Scenario	Truck availability	Regional bases	Plants	Raw material type	Harvest areas	Demand
1	50	1	1	1	5	100
2	120	1	1	1	5	300
3	400	1	1	1	5	1000
4	50	1	3	1	5	100
5	120	1	3	1	5	300
6	120	1	5	1	5	300
7	300	1	5	1	5	750
8	70	5	1	1	10	150
9	200	5	1	1	10	500
10	70	5	3	2	10	150
11	200	5	3	2	10	500
12	70	5	5	3	10	150
13	200	5	5	3	10	500
14	100	12	1	1	15	200
15	400	12	1	1	15	750
16	500	12	2	2	35	1000
17	100	12	3	3	15	200
18	100	12	5	5	15	200
19	400	12	5	5	15	750
20	400	12	6	3	15	750

profitability of firms, given the large volumes that must be transported and the distances that must be traveled. Forest industry presents specific characteristics that generate many routes: the number of harvest areas, many regional bases given a large number of small truck companies that provide the service and a dense network of roads to access

Table 11
Model statistics for each scenario.

Scenario	Continuous variables	Discrete variables	Equations	Used trucks	CPU time (s)	GAP
1	51	2,450	3,906	34	1.12	0.00%
2	121	5,880	9,366	110	79.19	0.00%
3	401	19,600	31,206	337	300.00	0.72%
4	51	5,750	9,008	34	1.62	0.00%
5	121	13,800	21,608	100	1.95	0.00%
6	121	21,720	33,850	100	10.15	0.00%
7	301	54,300	84,610	250	31.14	0.00%
8	71	6,580	9,667	50	0.42	0.00%
9	201	18,800	27,607	167	2.78	0.00%
10	71	15,400	23,119	50	1.70	0.00%
11	201	44,000	66,019	167	55.14	0.00%
12	71	24,220	36,571	50	3.91	0.00%
13	201	69,200	104,431	167	28.81	0.00%
14	101	13,900	19,805	67	0.92	0.00%
15	401	55,600	79,205	250	2.98	0.00%
16	501	266,000	379,561	334	300.00	0.03%
17	501	32,500	48,037	67	116.62	0.00%
18	101	51,100	76,269	67	90.31	0.00%
19	401	204,400	304,869	250	300.00	0.04%
20	401	241,600	361,240	250	247.76	0.00%

forests. Then, the combination of possible routes is huge, which generates a highly combinatorial problem. A reliable supply of logs that allows for the availability of the right timber at the right time, in the right place, is a competitive advantage.

In the Argentine context, companies generally make decisions regarding the distribution of logs based on their experience, i.e., heuristic solutions. Therefore, the use of a planning tool to make these decisions substantially improves the obtained results and the performance of the truck fleet. Taking into account this context, a MILP model for product allocation and vehicle routing in forest industry was presented in this work. The proposed formulation allows generating simultaneously all the possible routes, avoiding the need of providing them beforehand through a long processing and resorting to big arrangements of data. Unlike the previous published works in the literature, the presented model simultaneously addressees such decisions and solves the overall formulation in a reasonable computation time.

Two study cases were analyzed and several scenarios were solved. The solutions obtained show that the MILP model can efficiently and effectively address log distribution objectives, with a high impact in the profitability of the forest industry.

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