COMBINATORIAL OPTIMIZATION APPLICATIONS IN CHILEAN LOG-TRANSPORT

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Combinatorial optimization applications in Chilean log transport

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ABSTRACT: *This paper describes two operations research (OR) techniques that were applied to the Chilean forestry industry. The work was conducted at one of the largest forest companies in Chile, Arauco S.A. The first application analyzed the operational effects of changes in the company shift policy in the transport area; a Bin Packing Problem solved by a heuristic was proposed to address this problem. The second application reassigned truck schedules made by outsourcing companies that mitigated the economic impact of the optimal reassignment; a heuristic that solves a Ranking Assignment Problem was proposed. This study aims to highlight the importance of adapting OR models and techniques to the needs and changes in the industry. The results show the feasibility and efficiency achieved by the proposed methods.*

KEYWORDS: *Forest industry, Bin packing problem, Ranking assignment problem*

1 INTRODUCTION

Timberlands of mostly pine and eucalyptus cover up to 2.1 million hectare in Chile, fueling pulp mills, sawmills, chips, panels and other industries. The forestry sector represented 2.5% of the GDP in Chile during 2012, with a transported volume of 39,075.2 $10^3 m^3 ssc$ (INFOR, 2013). Ground transportation, primarily with trucks, is typically employed because it easily connects operations between the harvesting fields and the industrial plants (Andalaft, et al., 2005). Within this context, Arauco S.A. is one of the major players in the Chilean forestry industry, with more than 40,000 employees in Chile, Argentina, Uruguay, Brazil, the United States and Canada.

Since the 1970s, Decision Support Systems (DSS) have been extensively used in the forest industry to solve different planning problems (Weintraub, et al., 1996). Numerous contributions from the operational research field, including applications in procurement, production, distribution and sales, can be found in existing literature (Weintraub, et al., 2008). Arauco S.A. currently uses ASICAM software to enable their daily truck scheduling (Epstein, et al., 1999). This software simulates a transportation day and heuristically assigns trips to trucks according to origin and destination requirements. The software returns a list for each truck indicating its origin and the plants to be visited each day.

The current evolution of the industry and the operating conditions of the company have given rise to other requirements not originally considered by ASICAM. For example, changes in the labor policies of the country have triggered the reduction of work schedules that involve changing the shifts of drivers. Trips that were originally performed by trucks with the same fare are now outsourced to several companies with different fares based on trip characteristics such as distance, road surface and contractual aspects.

This work presents two applications of classic combinatorial optimization models that address these issues in order to adapt to the changing needs of the company while complementing the solutions of the DSS. The first problem involves evaluating changes in the shift policy of transport activities by considering the economic implications for the interested groups. To address this issue, a heuristic procedure that solves the related Bin Packing Problem performs simulations to analyze the operational effects of the shift changes. The second problem involves proposing new trip assignments by considering cost variations among the outsourcing transport companies. The practical concerns are the quality of the service and obtaining a solution that does not favor one company over the others with respect to the original assignment; in other words, the effect of the optimal assignment must be dampened.

Although many logistical problems in the forest industry have been addressed by using OR techniques with efficient results, current industrial practices must adopt conventional techniques to address changing industry environments and needs. Therefore, the aim of this work is to show, through two actual applications, how conventional OR techniques can be incorporated to meet current company needs.

The first problem concerns the work shifts of truck drivers and is solved through a Bin Packing Problem as explained in Section 2. The second problem concerns the assignment of daily truck schedules and is solved through a Ranking Assignment Problem as explained in Section 3. Section 4 presents the major conclusions of this work.

2 SIMULATION OF SHIFTS THROUGH THE BIN PACKING PROBLEM

The company is interested in knowing how the number of trucks and the trips per truck will change if the shift policy changes to three shifts of 8 hrs. each—an increase of one hour per shift. They are also interested in studying the impact on the number of trucks and trips per truck if the loading and unloading times are reduced. The truck drivers are interested in the number of trips they can perform during a shift because a portion of their incomes is proportional to this indicator. If the altered shifts imply a reduction in their incomes, then they will not agree to the change (Forestal Arauco S. A., 2012).

To answer these questions, the total trips performed during a month were studied to focus on the exchange between shifts. Arauco S.A. uses ASICAM software for their daily truck scheduling, with two daily shifts of 11.5 hrs. per truck. Although the arriving and departing times to the harvest field and plant were known, the travelling time to the harvest field was unknown for many trips; it was approximated from the travelling time from the harvest field to the plant. Each trip was modeled as the traveling time to the harvest field, the loading time, the traveling time to the plant and the unloading time.

Figure 1 shows the number of trips, the number of trucks and the average of the rate of trips per truck for each day.

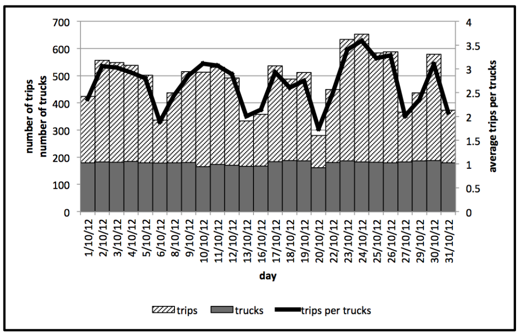

Figure 1: Number of trucks and trips.

The average number of trips per day was 483.04, with a standard deviation of 97.64 trips. The average number of trucks per day was 178.54, with a standard deviation of 7.21 trucks. The number of trips per truck was in the range [1,7], with an average of 2.69 trips.

2.1 Modelling the problem

The approach to the problem relies on the premise that the trips can be efficiently scheduled into the shifts so as to perform more trips during a shift. A Bin Packing Problem (BPP) was used to simulate the shifts. This problem seeks to pack a given set of objects into a minimum number of bins. Each bin has a limited capacity that is used by the objects.

The trips were thus grouped into the minimum number of shifts by considering the length of the shift as the capacity used by the length of the trips. In studying the number of trucks and the trips per truck, we assumed that each truck performs two shifts daily according to current policy.

If m represents the number of trips performed during a day, each trip i with a length d_i; and n the number of shifts, each shift j with a length D; then the mathematical model representing the problem is (Martello, and Toth, 1990):

$$
\begin{array}{rlll}
BPP = min & \sum_{j=1}^{n} y_j & & (1) \\
s.t. & \sum_{j=1}^{n} x_{ij} = 1 & i = \{1, \ldots, m\} & (2) \\
& \sum_{i=1}^{m} d_i x_{ij} \leq D y_j & j = \{1, \ldots, n\} & (3) \\
& x_{ij} \in \{0, 1\} & i = \{1, \ldots, m\} & (4) \\
& y_j \in \{0, 1\} & j = \{1, \ldots, n\} & (5)
\end{array}
$$

where the binary variable x_{ij} indicates that trip i is assigned to shift j and the binary variable y_j indicates that shift j is used.

To solve the BPP, we implement a First Fit heuristic (FF) (Fekete, et al., 2001). This heuristic arranges the trips in non-increasing order according to their length and, following this sequence, assigns them to the first shift with sufficient available time. A new shift is added each time that there is no available time in any of the shifts for the current trip. This is one of the best-known heuristics for general instances of the BPP (Dokeroglu, and Cosar, 2014). Using a merge sort to order the list of trips, the time complexity of the heuristic is $O(nlogn)$. For the quality of the solution, the asymptotic worst-case performance ratio is $r^{\infty}(FF) = \frac{17}{10}$ (Martello, and Toth, 1990). The drawback of this heuristic in this particular application is that it does not balance the number of trips assigned to each shift, meaning that there could be a high variability in the number of trips assigned to each shift.

To determine the quality of the solution in terms of the number of trucks, a continuous relaxation of the problem was used as a lower bound (LB). This lower bound was calculated as the sum of the length of all the trips divided into the length of the shifts, and then divided into the number of shift c that a truck can perform in a day.

$$LB = \frac{\frac{\sum_{i=1}^{m} d_i}{D}}{c} \tag{6}$$

2.2 Shift modification

Figure 2 shows the number of trucks (dark columns) needed to perform the shifts if each truck can perform two shifts daily ($c = 2$). The LB value (hatched columns) overlaps the column with the number of trucks. The average difference between them is 0.88%, meaning that the heuristic performed very well in these instances.

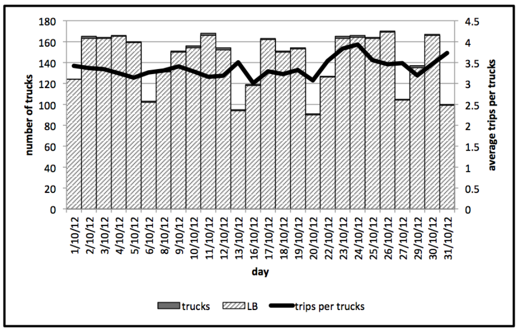

Figure 2: Simulation with current length of shifts.

The average number of trucks per day is 143.00, with a standard deviation of 26.3 trucks. This rate translates to a decrement of 19.95% in the number of trucks needed per day. The average number of trips per truck is 3.38, with a standard deviation of 0.22 trips, indicating 25.65% more trips per truck than the company's schedule currently employs.

Figure 3 shows the results for changing the length of the shifts to 8 hours with three shifts daily ($c = 3$), thus increasing the shift length by one hour. The average number of trucks per day is 137.04, with a standard deviation of 25.21 trucks, requiring 23.29% fewer trucks than the original schedule. The average number of trips per truck is 3.52, with a standard deviation of 0.23 trips.

The differences obtained between the company's schedule and simulation results are due to two factors: the approximation of the traveling times and the BPP solution's efficient trip schedule. In the last simulation, the difference can also be explained by the extra hour of work in each shift.

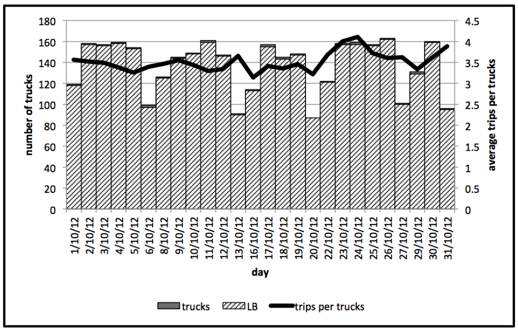

Figure 3: Simulation with 3 shifts of 8 hours.

2.3 Reduction in loading and unloading times

To conclude the study, we simulate the effect on the number of trucks and trips per truck if the loading and unloading times are reduced by 10%, 20% and 30% for the policy with two shifts.

Table 1 shows the results for the average number of trucks needed and the average number of trips per truck in the three simulations.

reduction	10%	20%	30%
trucks	138.00	133.38	128.62
trips per trucks	3.50	3.62	3.75

Table 1: Results for the reductions in time.

The results show that improving the loading and unloading times uses a smaller number of trucks and consequently increases the number of trips per truck.

According to the results of the study, the change in shift policy would maintain or improve the number of trips per truck if the trips were efficiently scheduled. A reduction in loading and unloading times would further promote this improvement.

3 ASSIGNMENT OF DAILY SCHEDULE THROUGH THE RANKING ASSIGNMENT PROBLEM

As previously mentioned, the trucks performing the trips belong to outsourced companies that charge different fares according to the covered distance and road surface. The existing software does not consider this difference in cost.

In this part of the study, Arauco S.A. is interested in reassigning trucks in order to reduce their total cost. However, other characteristics that must be addressed in the new assignments, such as the quality of the service, cannot be generally quantified. In addition, there are existing contracts in effect with the outsourced companies, and a severe reduction in cost could result in conflicts with several pressure groups. Accordingly, our approach provided a sequence of assignments with increasing costs alongside the minimum cost assignment; in this way, the decision maker could select the best performing solution.

Unlike the previous study, the trips performed by a truck in one day cannot be modified, i.e., modifying the sequence of trips. The problem was framed by allowing the interchange of daily truck schedules. This set of trips that a truck must perform in a day was called a program.

3.1 Modeling the problem

A semi-assignment problem (SAP) (Kennington and Wang, 1992) was used to model the problem. This is a particular case of the Classic Assignment Problem, where a set of m objects must be assigned to a set of n entities ($n < m$), each of them with a defined capacity. The cost of the assignment depends on the object and the entity, and the objective is to minimize the total cost of the assignment. The problem can be mathematically expressed as:

$$SAP = min \quad \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{7}$$

$$s.t. \quad \sum_{j=1}^{n} x_{ij} = 1 \qquad i = \{1, \ldots, m\} \tag{8}$$

$$\sum_{i=1}^{m} x_{ij} = d_j \qquad j = \{1, \ldots, n\} \tag{9}$$

$$x_{ij} \in \{0, 1\} \qquad i = \{1, \ldots, m\}, \quad j = \{1, \ldots, n\} \tag{10}$$

In the studied problem, the programs (i) correspond to the m objects. The trucking companies (j) are the n entities, each with a defined number of trucks d_j. Obviously, $\sum_{j=1}^{n} d_j = m$. The cost of the program is i if it is performed by a truck of company j, is represented by c_{ij} and the decision to assign the program i to a truck in company j is represented by the binary variable x_{ij}.

Figure 4 presents a diagram of the problem. The programs are represented in the set on the left, whereas the companies are represented with the dark sets on the right.

Each company has a set number of trucks. A given program has the same cost in any truck of the company. In the figure, the costs are represented with the lines and lines of the same type represent the same cost. To simplify the figure, only the costs for one program are represented. Only one of these lines is selected for the assignment of that program.

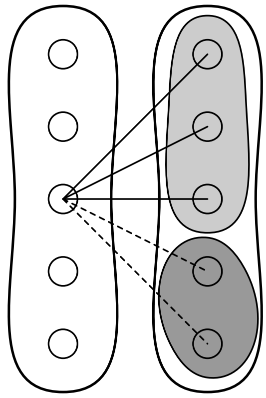

Figure 4: Assignment of programs to trucks.

As SAP is a particular case of the Classic Assignment Problem, it can be solved in polynomial time $O(n^3)$ (Papadimitriou and Steiglitz, 1998) with a successive shortest path procedure. To find a proposed list of assignments for Arauco S.A., the Ranking Assignment Problem (Burkard, et al., 2009) provides a sequence of solutions with non-decreasing costs in $O(Kn^3)$ (Chegireddy and Hamacher, 1987; Pascoal et al., 2003) where K is the number of solutions in the sequence.

Although the exact methods can be used to find a sequence for the SAP, they are not very efficient in solving the Ranking Assignment Problem (Murty, 1968), (Pedersen, et al., 2008) because the symmetry of the problem leads to many equal solutions. As a result, K must grow, thus increasing the computing time.

We propose a specific heuristic suited for the SAP to solve the ranking problem. This heuristic is based on the observation that the total cost will remain the same if a program is assigned to any truck of the same company. With each iteration, the heuristic solves an instance of the Classic Assignment Problem with modified costs forbidding some assignments. When the number of solutions needed or the time limit is reached, the heuristic stops.

3.2 Experiments & results

To evaluate the performance of the heuristic, a set of 50 instances from the actual problem was used.

The parameters describing the instances are as follows:

- number of programs for day m, in the range [102, 293].
- number of truck companies n, in the range [6, 21].
- number of trucks per company d_j, in the range [1, 45].

Because the exact sequence is unknown, the heuristic is evaluated in terms of the number of different solutions in the sequence and the average closeness between consecutive solutions. The number of different solutions in the sequence is a measure of the diversity of solutions found by the heuristic. Ideally, all the solutions in the sequence are different. The average closeness between consecutive solutions indicates whether the solutions not found by the heuristic are relevant. If the difference between solutions is significant, the heuristic is likely leaving many solutions unexplored. In Table 2, we present the modified cost results because of privacy reasons. For this test, the stopping criterion was set to 60 seconds.

The first column, $Instance$, corresponds to the name of the instance $n \times m$ that describes the number of trucks and companies. The instances are initially ordered by a non-decreasing number of trucks, n, and then by a non-decreasing number of companies, m. The second column, n_{sol}, indicates the number of solutions in the sequence. The third column, n_{dif}, indicates the number of different solutions. The fourth column, $\bar{dif}$, indicates the average difference between consecutive solutions. The last column, $time$, reports the computation time in seconds.

The results show that the number of solutions in the sequence is in the range of [25,97] and the number of different solutions is in the range of [23,93]. In 64% of the instances, all the solutions in the sequence are different. For instances with repeated solutions, the number of repeated solutions is in the range [1,5], representing 5.52% of the number of solutions in the sequence, on average.

The average of the difference between consecutive solutions is 54.31, which is smaller than the lower bound in the range of costs. The time limit is reached for all instances.

It can be seen that n_{sol} and $n_d if$ are different for some instances with the same number of trucks and companies. This outcome occurs because some companies have identical costs; the heuristic does not distinguish between them.

In Figure 5, we show the difference in cost for one instance. The cost of the original solution is represented with the horizontal line at the top, and the sequence of solutions found by the heuristic is represented with the diamonds. The sequence shows that some of the solutions are repeated and the cost does not decrease.

For each of these solutions, the decision maker can compare the difference in terms of cost for the outsourced companies while knowing how the change affects them. In this way, Arauco S.A. can reduce transportation costs without causing conflicts with outsourced companies.

$Instance$	n_{sol}	n_{dif}	$\bar{dif}$	$time[s]$
197 x 13	97	93	168.60	60.01
208 x 15	78	78	60.47	60.72
233 x 18	60	59	63.70	60.90
246 x 19	44	42	40.14	60.79
251 x 18	40	40	77.31	60.92
252 x 18	47	42	31.72	60.67
254 x 17	35	35	32.62	60.52
256 x 16	35	35	59.91	60.55
261 x 16	36	36	58.65	61.10
262 x 17	36	36	62.43	60.11
262 x 17	35	35	53.59	60.64
263 x 19	37	37	64.77	60.81
264 x 17	33	32	50.53	61.63
265 x 19	33	33	46.94	60.46
266 x 17	35	35	59.48	61.08
266 x 19	33	33	76.02	60.08
270 x 19	32	32	37.73	60.61
270 x 19	33	33	63.78	61.16
270 x 20	34	34	77.23	61.23
271 x 19	33	33	31.46	60.35
271 x 19	34	34	73.49	61.69
272 x 19	30	30	56.45	60.62
273 x 18	29	26	31.98	61.55
273 x 19	33	31	35.97	61.79
273 x 19	32	32	54.10	61.23
273 x 19	32	30	39.14	60.57
274 x 19	30	29	46.26	61.02
275 x 18	29	28	41.72	60.32
277 x 18	28	27	46.57	61.86
277 x 19	30	29	60.92	61.73
278 x 18	26	26	58.83	60.97
278 x 18	28	26	46.04	60.92
278 x 19	28	28	65.91	61.49
279 x 18	30	26	52.22	61.55
281 x 20	31	30	51.14	60.19
281 x 20	29	29	77.32	62.10
282 x 20	26	26	47.80	62.12
282 x 20	28	28	42.01	60.24
283 x 20	27	27	66.31	61.26
284 x 18	26	26	51.31	62.08
284 x 19	25	23	47.85	60.00
284 x 19	27	26	35.66	61.97
284 x 20	27	27	57.55	61.21
285 x 19	28	27	33.44	61.92
285 x 19	27	27	39.35	60.67
285 x 19	27	27	48.68	60.59
285 x 19	29	29	49.29	61.52
287 x 19	25	25	29.66	60.01
288 x 21	26	26	63.34	60.38
290 x 19	25	25	48.05	61.92

Table 2: Results of the Ranking Assignment Problem.

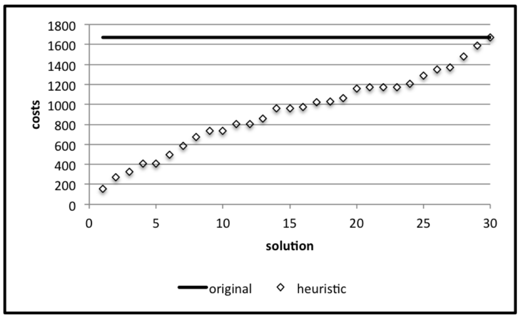

Figure 5: Cost difference between original and heuristic solutions.

4 CONCLUSIONS

This paper presents two applications of combinatorial optimization to problems arising in the forest transportation industry in Chile.

The first application uses a Bin Packing Problem to study different configurations of driver shifts and loading and unloading times. The results indicate that the number of trucks can be improved by changing the sequence of the trips in the schedule; as a consequence, the number of trips per truck would increase and have a positive impact on driver incomes.

In the second application, a Ranking Assignment Problem is solved to provide a sequence of different solutions for the decision maker that considers the different costs of outsourced trucking companies. A suited heuristic is presented because the symmetry in the solutions avoids the use of exact methods. The primary advantage of this application is that the decision maker has many solutions that consider the different fares of the trucking companies and can select the best suited for the day.

These results show the feasibility and efficiency of procedures that use OR techniques to complement a DSS and adapt solutions to the needs that the present environment imposes on the forestry industry. This need falls under the perspective of a continuous improvement of business processes to maintain a competitive advantage in a demanding market.

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