MULTIPLE CRITERIA DECISION-MAKING APPROACH TO SUPPORT TIMBER TRANSPORTATION PLANNING – CASE STUDY IN BRAZIL

By

Marinna Lopes Ferreira Gomes

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Committee Membership

Dr. Kevin Boston, Committee Chair

Dr. James Graham, Committee Member

Dr. Harold Zald, Committee Member

Dr. Erin Kelly, Graduate Coordinator

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ABSTRACT

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Timber transportation is one of the costliest activities for a forest company in Brazil and in many other countries, and it is a determining factor for the success of the forest enterprise. Thus, decision support tools are commonly used as methods to reduce these costs. The purpose of this study was to develop and analyze mathematical models to define the weekly timber transport schedule based on the monthly demands of the customers. The goal is to minimize the operational costs of forest transportation related to distances, timber freshness and road qualities. The decision process was made in two steps; the first was to select the timber location to be transported in a month, according to the client´s demand and timber stocks in the landing area. The second is to develop a weekly timber transportation scheduling to implement the monthly schedule. In the monthly decision process, three approaches in operational research were analyzed: multi-objective linear programming (MOLP) and two lexicographic multi-objective linear programming models (LMOLP 1 and LMOLP 2) with objectives in different hierarchical orders. The models were implemented in OPL (Optimization Programming Language) and its solution obtained using the software IBM ILOG CPLEX Optimization Studio. In the second part, the weekly timber scheduling, the decision process was taken to truck trips per week, ensuring timber transportation according to the customer's desired post-harvest age and a balance of truck trips per week. In this second stage, a Lexicographic Goal Programming model was developed due to a clear priority ordering amongst the goals to be achieved, in which in the sum of days left to deliver the timber from week 1 will be less than week 2; week 2 will be less than week 3; so on. The model was applied in the software *Lindo*.

The results obtained from the monthly decision-making process reveal that the flexibility of the lexicographic models demonstrate a great potential for reduction in costs. Total costs for the LMOLP 1 model were 30% less than the cost resulting from the MOLP model, and 9% less than the LMOLP -2 model. Regarding the second decision-making process, the lexicographic goal programming was highly suitable to solve weekly planning problem with complex multi attribute nature.

Keyword: Timber Transportation, Operations Research, Timber truck scheduling, Multi Objective Linear Programming, Lexicographic Multi Objective Linear Programming, Lexicographic Goal Programming.

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I dedicate this work to my daughter Maya.

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1. INTRODUCTION

The total planted forest area in Brazil is 7.83 million hectares, which represents less than 1% of the Brazilian´s territory (IBGE, 2017), but supplies 96% of the domestic timber demand for various purposes. The Brazilian planted tree sector, which corresponds to monocultures forest, usually *Eucalyptus* and *Pinus*, supplies wood flooring, paper and cellulose pulp, lumber, and charcoal. In 2018, this sector showed a 13.1% increase in Brazilian gross domestic product (GDP) over the previous year, reaching a total revenue of approximately U$ 21.72 billion (R$ 86.6 billion in Brazilian currency) (Ibá, 2018). The growth in this sector was much higher than the national average, which recorded at 1.1% increase in gross domestic product (GDP), while farming and agriculture and livestock grew 0.1%, the service sector expanded 1.3%, and industry of all types grew 0.6% (Ibá, 2018).

In 2018, an average productivity for *Eucalyptus* plantations was 36.0 m^3 / ha.year, and 30.1 m^3 / ha.year for *Pinus* plantations (Ibá, 2018). For comparison, the estimated average productivity of *Giant sequoia* planted in California in the United States is 11m^3 / ha.year (Libby, 1992). By the end of the growing process, all the timber needs to be transported from the forest to the processing centers.

1.1. Timber transportation

The major steps in the forest production cycle cover the process of acquiring the area, preparing the soil, planting the seedlings, soil fertilization maintaining, harvesting, and timber transporting. Timber transportation represents the end of the forest production cycle, and can be divided into two stages. The first stage, known as primary transportation, includes the yarding or skidding corresponds to all activities from felling to the landings. It moves the timber from the harvesting site to the landing area, usually along roadside (Demir, 2010). The second stage, known as the principal timber transportation or secondary hauling which the post-harvested timber from the landing area is loaded by trucks on forest roads to an intermediate storing place or directly to the mill (Van Wyk, 2010).

Principal timber transportation can be performed by road, water, or rail. In Russia and Canada, timber transport by rail is the most widely used, accounting for 81% and 46% respectively (Machado et al., 2009). However, in many countries road transport is the prevailing one. In Brazil, 85% of timber is transported in trucks by road (Stein et al., 2001), in Ghana 90% (Abeney, 2003), and 76% in Finland (Finnish statistica ,2012).

Although transportation is at the end of the harvest rotation, which can last about seven years on *Eucalytus* plantations in Brazil (Rodigherí, 1997), or more than 100 years on Redwood (*Sequoia sempervirens*) forest in California, the principal timber transportation is one of the most costly activities for a forest company. Transportation costs represent more than 25% of the forestry industries´ roundwood procurement costs in Sweden (Svenson and Fjeld, 2016), 20 to 30% in New Zealand (Carson, 1990), and about 30% in Germany (von Bodelschwingh, 2001). Studies in Brazil reveal that the transportation cost is around 40% of the costs of the extraction costs incurred by the forestry company (Malinovski and Fenner, 1986).

The high cost is associated with several factors, and the distance traveled on the principal timber transport is one of the factors that most affect transportation costs, whether by road, rail or waterway (Leite, 1992). Loading and unloading time is another factor that influence the cost of transportation (Marques, 1994), These costs are also influenced by the vehicle type, road quality, and weather conditions, which impacts to road conditions and influencing the safety in the load to be transported (Leite, 1992; Berger et al., 2003).

In order to improve timber transportation and all other forest management activities, the planning decision-making can be performed using a hierarchical structure. Information is passed from the top-down in this hierarchy, according to the time scale, and the decisions are used in at each level below. These hierarchy levels are traditionally denoted as: strategic, tactical, and operational (Weintraub and Bare, 1996; Martell et al., 1998; Silva, 2015).

Strategic planning is at the highest level of the hierarchy, and include long-term, large-scale goal setting (Bettinger et al., 2016), which is generally equivalent to a one-and-a-half-time horizon of two rotations of a forest (Clutter et al., 1983). Although the considerations differ between organizations and countries, strategic planning usually includes the goal of ensuring long-term stability in the wood supply to industries while maximizing the net present value (Martell et al., 1998). For the forest transport sector, examples of activities that are decided at this level are related to infrastructure (e.g. road network) and the selection of transportation modes (e. g. by train, road, ship) (Audy et al., 2013).

Usually, in tactical planning, forest transport decisions are made about the upgrading of the transportation infrastructures (e.g. increasing the terminal storage capacity) and the adjustment of the transportation equipment capacity and aggregated utilization level (e.g. number of wagons in the train route) (Audy et al., 2013). In general, forest planning decisions are made about spatial aspects of harvest volumes, harvest sequence, and machinery that will be used, and their costs and yields (Machado, 2014).

Operational plans are at the lowest level of the planning hierarchy, describing specifically how each activity will be implemented (Boyland, 2003). It covers the shortest time horizons, in which the activities to be performed by the work teams and machines are decided. This level of planning deals with various uncertainties and unforeseen situations, being the edge between planning and execution activities. In the forest transport sector, operational decisions deal with volume allocation from supply points to demand points, truck routing, and transportation scheduling of equipment and crew (Audy et al., 2013).

Overall, strategic plans reviewed annually or every other year, as the need to reevaluate an organization's strategic position is infrequent. By contrast, the tactical and operational plans, which consists of finding more efficient ways to achieve strategic objectives, are more flexible and able to respond to changing information and conditions, as they deal with unforeseen situations (McDill, 2014).

1.2. Operational Research Models for Forest Planning

Operations research (OR) is a scientific approach to decision making that seeks to best design and operates a system (Winston and Goldberg, 2004). The term operations research was developed during World War II from the need to deal with problems of a logistical nature, tactics, and complex military strategy. The scientific approach to decision making usually involves the use of mathematical models, that is, mathematical representation of a current situation that may be used to make better decisions (Winston and Goldberg, 2004). Using mathematical modeling techniques and efficient computational algorithms, OR can assist the decision-maker in analyzing the most varied aspects and situations of a complex problem, allowing effective decision making.

In the forestry area, operational research modeling has been used to solve a variety of forestry problems since the 1960s, and has evolved greatly with technological advances. Several areas in forestry use OR to support decision-making, such as forest management (Balana et al., 2010), supply chain planning (D'Amours, et al., 2008), timber bucking (Marshall et al., 2006), harvest scheduling (Díaz-Balteiro and Romero, 1998), and transportation planning (Forsberg and Rönnqvist, 2005).

The challenges of planning forest transport are deciding where the logs come from, what the destination is, when to transport and how much timber to transport. The most common goal is to minimize overall costs. Although these questions may seem simple, their answers are hampered by the numerous and complex scenarios that exist in forest companies (Guera, 2017).

1.2.1. Linear programming models for forest planning (LP)

Among the techniques within Operations Research, Linear Programming (LP) is one of the most important technique being used (Zionts, 1974). Since the 50s, LP has been used to solve optimization problems in industries as diverse as banking, education, forestry, petroleum, and trucking (Winston and Goldberg, 2004). A mathematical model in Linear Programming is developed to determine the values of a set of continuous variables, aiming to minimize or maximize a single linear function (single objective function) while satisfying a set of linear constraints (Lachtermacher, 2016). In forestry studies, Berger et al., (2003) successfully implemented a minimization of forest transport costs using Linear Programming models, in the city of Canoinhas, in the State of Santa Catarina, southern Brazil.

Multi objective linear programming (MOLP)

Industrial problems often have multiple objectives. Multi-objectivity (or multicriteria) is also common for current forestry problems (Ostadhashemi et al., 2014), in which there are often conflicting objectives, such as forest harvesting planning, where it is wished to minimize costs, and attend the spatial adjacency restrictions of forest stands (Pereira, 2007). Thus, multiobjective linear programming (MOLP) is the one of the most traditional way to solve a problem with multi objective to be reached (Du, 2008), in order to minimize or maximize a multi-linear function. In this method, multiple objectives are combined in a single objective function, and require a set of weights. The search for correct weights can be very time-consuming (Cococcioni and Sergeyev, 2018).

Lexicographic multi objective linear programming (LMOLP)

Another LP approach for solving multi-objectives models is Lexicographic Multi Objectives Linear Programming (LMOLP). Unlike the MOLP, in the LMOLP there is a hierarchical order of optimization, in which the first objective is optimized, then the second, and so on, until deviations from all the goals have been minimized. The higher priority goals are solved first and become constraints preventing any less attainment in the later periods. This methodology is interesting since there is no need to set weight for variables, but rather an order of optimization preference (Cococcioni and Sergeyev, 2018). In problems with no hierarchical order of optimization, or if two or more objectives have the same priority, this model is not indicated.

Goal programming

Goal programming (GP) is a branch of multiobjective optimization. GP is the modeling that aims to find a solution by minimizing the deviations from the targets or goals. Goal programming models can also have a hierarchical order to achieve the goals. In this case it is called Lexicographic Goal Programming where the goals are assigned a hierarchy of importance.

1.3. Objectives

The purpose of this study was to develop and analyze mathematical models to define the weekly timber transport schedule based on the monthly demands of the customers. The goal is to minimize the operational costs of forest transportation related to distances, timber freshness and road qualities.

1.4. Limitations

The limitations that permeate this research was the non-availability of some of the costs inherent to the process by the company whose case study is the focus of this research. Thus, the costs obtained at the end of the tests do not faithfully reflect the current conjuncture found in the company. However, the purpose of this research is to develop the mathematical model, so this limitation did not prevent the work from being completed.

2. MATERIALS AND METHODS

The work followed the predicted phases of the Research Operations project (Figure 1). From the definition of a real problem, the mathematical model was developed, and tested with data. Large-scale implementation and testing have not been done in this research but is suggested in future work.

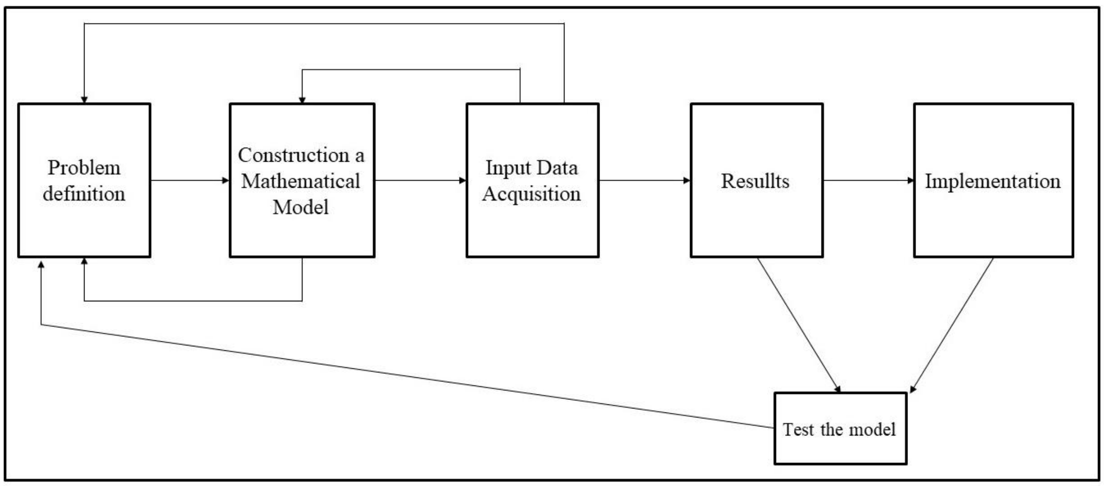

Figure 1: Phases of Operation Research project

The question that inspired and motivated this research is the problems faced by a forest company in Brazil regard to the principal timber transportation planning. To protect the company's interest, strategies and planning, the data was randomly created, and the actual locations of customers and the company´s name were omitted. In this research, all the data are hypothetical, and the main contribution of this work is the development of mathematical models describing the approaches to conduct hierarchical planning approaches to minimize forest transport costs in the proposed scenario.

The timber transportation problem is a two stages decision process. The first stage refers to the definition of timber stock locations that will meet the monthly demands of customers. From the first stage results, the second stage consists of defining the weekly timber delivery schedule.

2.1.The first stage of the decision process – the monthly planning

The goal of the first stage is to identify the timber location to be transported in a month, according to the customers ´ demand, minimizing cost (Figure 2). In order to achieve this goal, the timber stock in the pick-up point must be sufficient to meet customer demand.

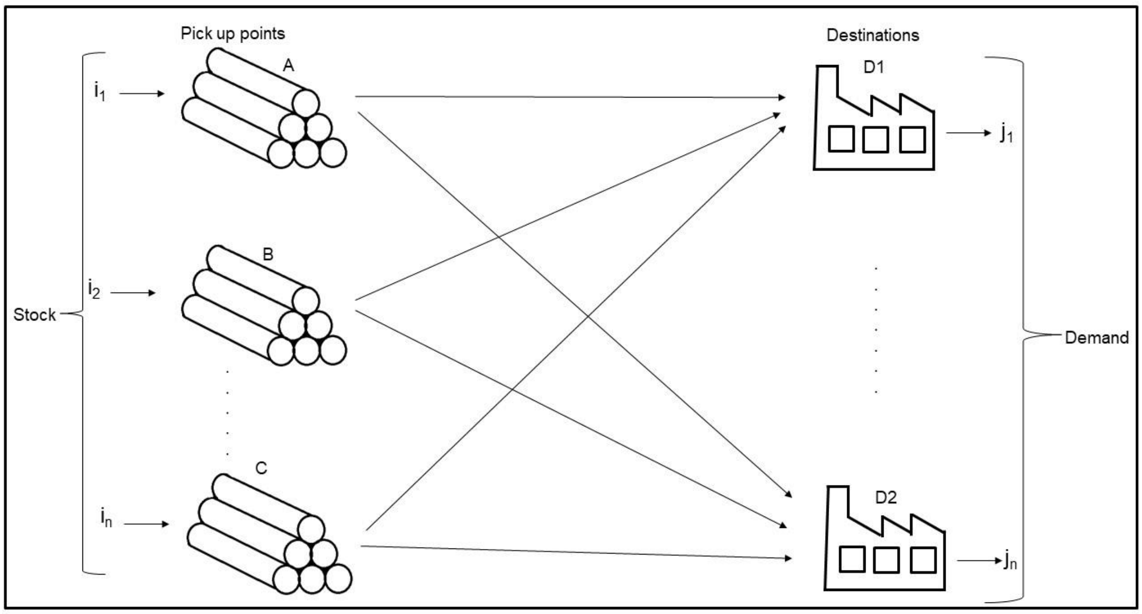

Figure 2: Timber transport model represented as a network with pick up point and destinations.

The pickup points or loading are the forest landing area. The customers have monthly demand for specific volume of a given forest product, with a given post-harvested age. The product is defined according to biological (species, average density, and diameter) and harvest (log size, and bark or without,) characteristics.

2.1.1. Timber cost transportation

The timber cost transportation in this research is related to the distance from pick-up point to destination, road quality from forest landing to highway, and post-harvest age (freshness). The results of the models will be transferred to an Excel spreadsheet so that the final cost will be calculated, considering the following costs:

2.1.1.1 Distance

The distance is measured according to the number of kilometers driven by volume from pick up point to the destination. In this model, we will consider the cost of $1 per ton*km to be transported. For example, if 10 tons of timber are transported from pick up point i_n to destination j_n, and the distance between i_nj_n is 50-km, the cost will be 10×50×1 = $ 500.

2.1.1.2 Road quality

The roads that connect the landing area (pick up point) to the highway have different qualities that impact their use. The roads with gravel, called R1, have better accessibility, and consequently generate lower trucks maintenance costs and allowed for use when wet. The R2 roads have no gravel and the soil is exposed, causing higher maintenance costs for trucks due to mud and may be inaccessible during wet weather. By choosing to use the R2 roads, there is a 30% increase in the cost of transportation, that is related to the distance. For example, if 10 tons of timber are transported from pick up point i_n to destination j_n, and the distance between i_nj_n is 50km, the cost will be 10×50×1 = $ 500. If the quality of the road is R1, the total value remains the same. If it is R2, 30% of the value is added, that is, the cost would then be $ 650.

Although the values are hypothetical, they are very close to reality (Notícia Agrícola, 2019). For coding in modeling, the roads R1 receive the value of 1, while R2 received value 2. Thus, by minimizing the variable roads we are prioritizing the use of roads R1, which have no extra cost.

2.1.1.3 Timber freshness

Each client has its tolerance for log freshness, that is, the age of post-harvest timber. This requirement varies according to the process the timber will be submitted to. For example, for a pulp and paper industry, post-harvest age is limited to 100 days. Older logs are drier producing lower quality chips and requires more chemicals and water be added to the pulping process. Some sawmills have a shorter time window for receiving timber, since dry timber (e. g.: more than 30 days post-harvest) can be easily cracked during the milling processes that reduce value recovery.

2.1.2 Modeling approaches for the monthly planning

To identify the timber´s origin to be transported (pickup point) for each customer, three modeling approaches in Operations Research were selected: Multi-objective linear programming (MOLP), and two models following the Lexicographic multi-objective linear programming (LMOLP 1 and 2).

To minimize transport costs, the objectives of the model are:

- Minimize distance between pick up point and destination, weighted by timber volume,

- Minimize the variable regarding to the roads, weighted by timber volume, so that the best quality roads (and consequently lower truck cost) are chosen.
- Minimize the timber days left to deliver (related to the freshness), weighted by timber volume.

These models have multiple objectives. The difference between the models is the degree of importance of each objective. The proposed MOLP model has three goals that were combined into a single objective function, where all are optimized at the same time, without preferential order or different weight assigned to them. In LMOLP models, there is a hierarchical order to be followed, in which after optimizing the first objective, the second is optimized, and successively.

Two variations of the LMOLP models were analyzed; in which there was a change in the priority of the model objective. In the first (LMOLP-1), the main objective was to reduce distances, then the variables related to road quality and then the freshness measures. In the second (LMOLP-2), the objectives were reversed.

For the models, the freshness was modeled as the remaining time allowed to deliver the timber to a customer. For example, the client's goal is to receive timber within 150 days following the harvest. In one landing area the timber was harvested 20 days ago, and in another area was 50 days ago. Thus, the time left to deliver corresponds to 130 and 100 days (150 - 20 and 150 - 50). To avoid timber loss, the goal is to select the older harvested timber, which is in the age range accepted by the customer, to be delivered first which means the lowest values of days left must be shipped first. For modeling, the objective will be to minimize the number of days left for timber delivery. This way, regardless of the freshness requirement by the customer, it will be easy to identify which timber should be delivered as a priority.

2.1.3 Mathematical models for the monthly planning

2.1.3.1. Multi objective linear programming (MOPL)

In this model, the three goals will be optimized as a single-objective function, that is, the model will provide the best results that achieve the three objectives simultaneously, not having priority to reach each objective, so they are all marked as "objective 1". All of them are weighted by c, that is equal to one (1) in this research. That is, they all have the same importance in optimization.

- **Objective 1**: Minimize distance between pick up point and destination weighted by timber volume,
- **Objective 1:** Minimize the variable with respect to the roads, weighted by timber volume,
- **Objective 1:** Minimize the timber days left to deliver, weighted by timber volume.

For the mathematical modeling, it required the sets, parameters and decision variables described in Table 1 to formulate and solve the problem.

Table 1: Set, parameters and decision variable used in the MOLP in the first decision making stage.

Sets
f: forest (pickup points);
Nf: total number of forests (pickup points);
e: destination (customers);

Ne: total number of destination (customers);
p: products
Np: total number of products;
Parameters
d_{fe}: is the distance from pick up forest f to the destination e;
a_{fp}: corresponds to the freshness of product p that is in forest f.
r_f: corresponds to the road quality is in forest f.
M_{ep}: corresponds to the demand (volume) from the customers **e** of the product p.
Sfp: corresponds to the stock (volume) of timber at forest f (pickup point) of the product p.
c: weight in the MOLP's objectives, in this case is equal to one.
Decision variables
X_{fep}: is the decision variables that express the volume to be transported from forest f to the destination e, taking the product p.

Objective Function

The single objective function (1) was created that combined the three objectives (distance, roads and freshness). For this model all objectives have an equal weight of one to not favor any goal over another, but they have different units.

$$Min \left(c\sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} d_{fe}\, x_{fep} + c\sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} r_f\, x_{fep} + c\sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} a_{fp}\, x_{fep}\right) \quad (1)$$

Constraints

In this model, there are two constraints. One in relation to the timber stock in the landing areas, and the other about the product demands required by the customers.

The stock constraint (2) is made to ensure that the volume to be transported is less than or equal to the volume in stock (at pickup points).

$$\sum_{e=1}^{Ne} x_{fep} \leq S_{fp\,,} \quad f = 1, \ldots., Nf; p = 1, \ldots, Np \tag{2}$$

The demand constraint (3) is made to ensure that the volume to be transported is greater than or equal to the customer's timber volume demand volume.

$$\sum_{f=1}^{Nf} x_{fep} \geq M_{ep\,,} \quad e = 1, \ldots., Ne; p = 1, \ldots, Np \tag{3}$$

2.1.3.2. Lexicographic multi objective linear programming (LMOPL)

For the mathematical modeling, it was considered the sets, parameters and decision variables described in Table 2.

Table 2: Set, parameters and decision variable used in the LMOLP in the first decision making stage.

Sets
f: forest (pickup points);
Nf: total number of forests (pickup points);
e: destination (customers);
Ne: total number of destination (customers);
p: products
Np: total number of products;
Parameters
d_{fe}: is the distance from pick up forest f to the destination e;
a_{fp} : corresponds to the freshness of product p that is in forest f.
r_f : corresponds to the road quality is in forest f.
M_{ep}: corresponds to the demand (volume) from the customers **e** of the product p.

Sfp: corresponds to the stock (volume) of timber at forest *f* (pickup point) of the product *p*.
Decision variables
X_{fep}: is the decision variables that express the volume to be transported from forest *f* to the destination *e*, taking the product *p*.

2.1.3.2.1. LMOLP 1

In the Lexicographic Multi Objective Linear Programming - 1 (LMOLP 1) model the lexicographic order of objectives are:

- **Objective 1**: Minimize distance between pick up point and destination weighted by timber volume,
- **Objective 2:** Minimize the variable with respect to the roads, weighted by timber volume,
- **Objective 3:** Minimize the timber days left to deliver, weighted by timber volume.

Objective Function

The objective function (4) for the lexicographic model considers the order of the goals presented for the execution of the problem.

$$LexMin \sum_{f=1}^{Nf} \sum_{e=1}^{Ne} \sum_{p=1}^{Np} d_{fe}\, x_{fep} \quad , \sum_{f=1}^{Nf} \sum_{e=1}^{Ne} \sum_{p=1}^{Np} r_f\, x_{fep} , \sum_{f=1}^{Nf} \sum_{e=1}^{Ne} \sum_{p=1}^{Np} a_{fp}\, x_{fep} \tag{4}$$

Constraints

This model, like the previous model, presents the constraints regarding stock and demand. The lexicographic optimization process is dynamic, and after optimizing objective 1, it makes constraints in the process and then resolves objective 2, and so on.

The stock constraint (5) is made to ensure that the volume to be transported is less than or equal to the volume in stock (at pickup points).

$$\sum_{e=1}^{Ne} x_{fep} \leq S_{fp\,,} \quad f = 1, \ldots., Nf; p = 1, \ldots, Np \tag{5}$$

The demand constraint (6) is made to ensure that the volume to be transported is greater than or equal to the customer's timber volume demand volume.

$$\sum_{f=1}^{Nf} x_{fep} \geq M_{ep\,,} \quad e = 1, \ldots., Ne; p = 1, \ldots, Np \tag{6}$$

2.1.3.2.2. LMOLP - 2

In the Lexicographic Multi Objective Linear Programming - 2 (LMOLP 2) model the lexicographic order of objectives is:

- **Objective 1:** Minimize the variable with respect to the roads, weighted by timber volume,
- **Objective 2**: Minimize the distance between pick up point and destination weighted by timber volume,
- **Objective 3:** Minimize the timber days left to deliver, weighted by timber volume.

Objective Function

The objective function (7) for the lexicographic model considers the order of the objectives presented for the execution of the problem.

$$LexMin \sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} r_f\, x_{fep} \quad , \sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} d_{fe}\, x_{fep}\, , \sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} a_{fp}\ x_{fep} \tag{7}$$

Constraints

This model presents the constraints regarding stock and demand. As previously mentioned, it is worth mentioning that the lexicographic optimization process is dynamic, and after optimizing objective 1, it makes constraints in the process and then resolves objective 2, and so on.

The stock constraint (8) is made to ensure that the volume to be transported is less than or equal to the volume in stock (at pickup points).

$$\sum_{e=1}^{Ne} x_{fep} \leq S_{fp\,,} \quad f = 1, \dots., Nf; p = 1, \dots, Np \tag{8}$$

The demand constraint (9) is made to ensure that the volume to be transported is greater than or equal to the customer's timber volume demand volume.

$$\sum_{f=1}^{Nf} x_{fep} \geq M_{ep\,,} \quad e = 1, \dots., Ne; p = 1, \dots, Np \tag{9}$$

2.1.4 Case study – First stage: monthly planning

To evaluate the models, a prototype example inspired by a large forestry company in Brazil was solved. The hypothetical scenario has five forests (pickup points), two products, and two destinations. The input data are shown in the appendix A.

At each pickup point there is only one product. The product is defined according to species, log size, with or without bark, average density, and diameter. In this research, forest products are identified as P1 and P2 (Table 3).

Table 3: Determination of forest products

Product	Specie	Log length	Bark	Density	Diameter
P1	*Eucalyptus sp.*	6.15m	No	high	greater than 25cm
P2	*Eucalyptus sp.*	7.20m	Yes	Indifferent	Indifferent

The distance between pick up point and destination, timber client´s demand, stock timber volume in the pickup point, roads quality, and days left to deliver the timber were randomly created in excel. The distances were randomly assigned between 0 and 150 km. Timber stock was randomly selected from 0 to 6500 tons; and the timber demands per product per customer were randomly assigned from 0 to 100 tons. The two customers (destination) have the same requirement of a maximum of 150 days post harvested, so the days left to deliver timber was assigned from 0 (150 days post harvested) to 150 (0 days post harvested). All these values were similar to values found in the spreadsheets of the transportation planning from the company that motivated this work.

The models were implemented in OPL (Optimization Programming Language) and its solution obtained by CPLEX Studio IDE 12.8 solver. In the LMOLP models was used the CPLEX Optimizer for Constraint Programming (CP). This optimizer allows lexicographic models to be solved directly (staticLex). The models were tested on a computer with the 10th generation Intel® Core ™ i7 processor and 8 GB of RAM. The scripts used are presented in the appendix B, C, and D.

2.2. The second stage of the decision process – the weekly planning

The goal of this second stage of the decision is to determine the weekly timber transportation schedule from the established in the monthly planning (Figure 3). This second decision process has the following constraint:

1) having approximately the same number of truck trip per week; that is, the number of truck trips per week will be approximately 1/4 of the total truck trips in the month, and
2) attending to the timber freshness requirement of each customer.

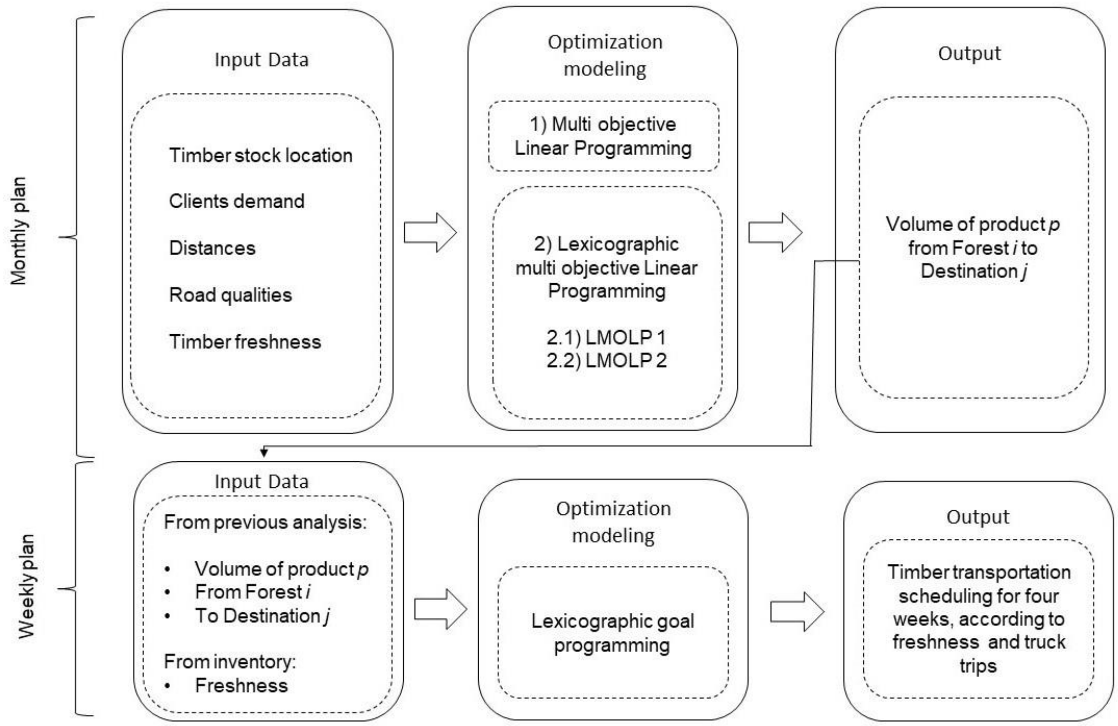

Figure 3: Flowchart methodology

In this second stage, the volume to be transported is categorized by number of truckloads trips (Figure 4). It was disregarded the trips with the empty truck and the way to the garage. To calculate the number of truck trips, the transported volume was divided by 40 tons, which is the average weight of a timber truck. The number of truck trips is integers, and eventually, the truck will be underused, since there is no transport of more than one product in the same truck. The timber is transported from the pickup point directly to the destination, with no refills along the way.

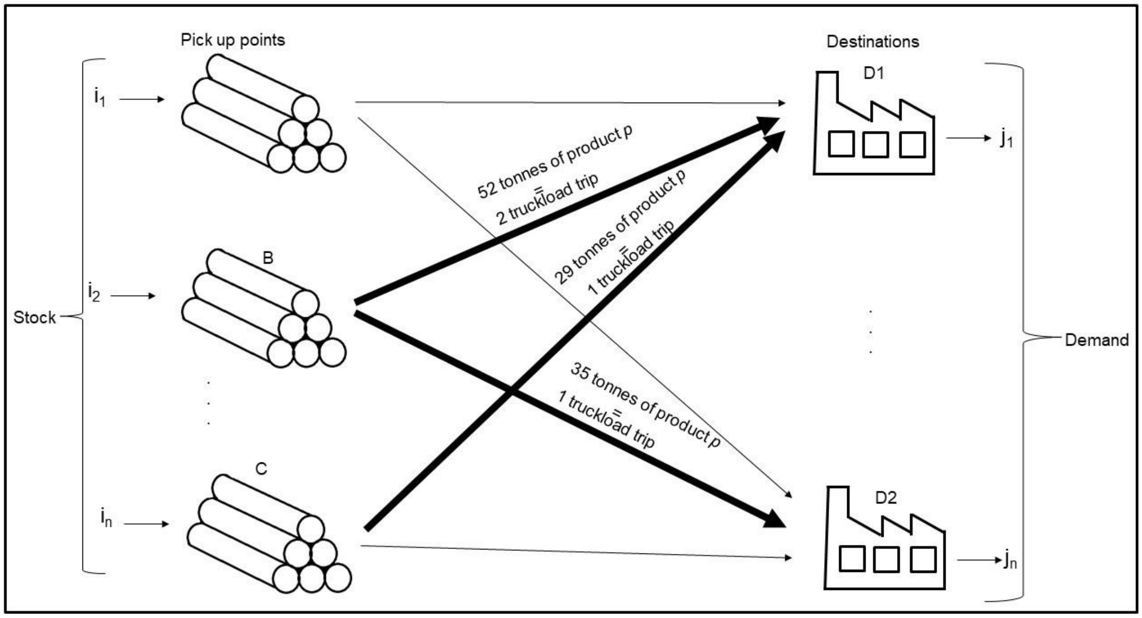

Figure 4: Example output from first stage decision process categorized by number of truckloads trips. The bold line represents the chosen combinations to the pickup point and the destination.

The freshness, which was also applied using the methodology in section 2.1.1.3, will be used to prioritize that longer post-harvest timbers must be transported earlier, to avoid timber losses. Each destination has its post-harvest age limit to receive the timber. For this model, as was done in part 1, instead of looking at the post-harvest age of the timber, we will look at the days left before the timber is on time, so the timber that is closest to the deadline should be shipped first.

2.2.1 Modeling approach for the weekly planning

To determine the weekly transport timber schedule was used the Lexicographic Goal Programming model approach (LGP). Unlike the models analyzed in stage 1, where it was desired to minimize costs by choosing the best timber pick up points, in stage 2 the goal is to minimize the deviations to reach the monthly target of timber delivery.

2.2.2 Mathematical model for the weekly planning

For the mathematical modeling, it was considered the sets, parameters and decision variables described in Table 4.

Table 4: Set, parameters and decision variable used in in the second decision making stage

Sets
f: forest (pickup points);
Nf: total number of forests (pickup points);
e: destination (customers);
Ne: total number of destination (customers);
Parameters
a_f: days left to deliver wood from the forest f;
T_{fe}: Number the trucks trip required from *f* to *e*
TT_{fe}: Total number the trucks trip required from *f* to *e*
Decision variables
p1: sum of the days left to deliver timber in the week 1
p2: sum of the days left to deliver timber in the week 2
p3: sum of the days left to deliver timber in the week 3
p4: sum of the days left to deliver timber in the week 4

Objective Function

The objective function expressed by the formula ten (10) has the function of lexicographically minimizing the sum of the days left to deliver timber per week. That is, the sum of days left to deliver the timber from week 1 will be less than week 2, so on. Thus, the timber with the shortest delivery time, to meet the customer's freshness requirements, will be delivered first, avoiding timber losses. Since we do not know what value it will represent each week, we call it p1, p2, p3, p4 for weeks 1, 2, 3, and 4, respectively.

$$LexMin\ [p1\ , p2, p3, p4] \qquad (10)$$

Constraints

The first set of constraint, the equations 11-14, refer to the sum of the number of days left to deliver timber during each week. The p1 values refer to the sum of the days left to deliver the timber at week 1, and follow the same principle for p2, p3 and p4**.**

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} af\ = p1\ \ , f = 1, \dots, Nf;\ \ e = 1, .., Ne \qquad (11)$$

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} af = p2\ \ , f = 1, \dots, Nf;\ \ e = 1, .., Ne \qquad (12)$$

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} af = p3\ \ , f = 1, \dots, Nf;\ \ e = 1, .., Ne \qquad (13)$$

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} af = p4 \ , f = 1, \dots, Nf; \ \ e = 1, .., Ne \tag{14}$$

The next constraint (15) refers to the number of truck trips that will be taken from each timber pickup point collection point to the destination. Each truck carries a maximum of 40 tonnes, so the number of truck trips from a given pickup point to the destination refers to the total volume to be transported divided by 40.

The number of constraints will be according to the number of forests and destinations. For example, if there are 5 forests and 2 destinations, there will be 10 equations (1 equation considering forest 1 for destination 1; 1 forest equation 2 for destination 1, and so on).

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} = T_{fe} \ , f = 1, \dots, Nf; \ \ e = 1, .., Ne \tag{15}$$

Equations (16-19) propose that the sum of the number of truck trips per week will be approximately 1/4 of the total trips in the month, having a balanced number of trucks trip per week. For example, if in one month there are nine timber loading truck trips, then at least two trips should be made per week.

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} T_{fe} \geq \frac{1}{4} TT_{fe} \ ; \ \boldsymbol{week\ 1}, f = 1, \dots, Nf; \ \ e = 1, .., Ne \tag{16}$$

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} T_{fe} \geq \frac{1}{4} TT_{fe} \ ; \ \boldsymbol{week\ 2}, f = 1, \dots, Nf; \ \ e = 1, .., Ne \tag{17}$$

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} T_{fe} \geq \frac{1}{4} TT_{fe}\ ;\ \boldsymbol{week\ 3}, f = 1, \ldots, Nf;\ \ e = 1, .., Ne \tag{18}$$

$$\sum_{f=1}^{Nf}\sum_{e=1}^{Ne} T_{fe} \geq \frac{1}{4} TT_{fe}\ ;\ \boldsymbol{week\ 4}, f = 1, \ldots, Nf;\ \ e = 1, .., Ne \tag{19}$$

2.2.3 Case study – Second stage: weekly planning

From the results of the first stage (monthly planning) a prototype was developed to validate the generic weekly model, by checking its functionality and consistency of the results. In this prototype there are five forest as a pickup point and two destinations. Table 5 demonstrates the input used to schedule truck trips. It is noteworthy that the lowest values of days left to timber delivery must be delivered in the first weeks, to ensure that the timber is delivered within the requirement related to freshness made by the customer.

Table 5: Input for weekly model

Forest	Volume (tons)	Product	Number of trips truck	Days left to timber deliver	Destination
1	200	P1	5	81	1
2	320	P1	8	112	2
4	455	P2	12	35	1
4	300	P2	8	35	2

The weekly planning timber transportation schedule was solved through the software LINDO version 6.1 and tested on a computer with the 10th generation Intel® Core ™ i7 processor and 8 GB of RAM. The complete formulation can be found in Appendix E.

3. RESULTS AND DISCUSSION

3.1 First stage of decision process - monthly planning

Each of the three models results in 20 variables. The MOLP model generates14 constraints, and the LMOLP models 1 and 2 generate 16 constraints. The computational time required to solve the MOLP model was about 10 seconds. To solve the LMOLP models, the computational time was longer, since the software searches for the best results from the established hierarchical order, and it was not possible to provide the results in less than 24 hours, so a 60 second timeframe was established.

The result of the decision variable for each of the three models is described in the table 6, 7 and 8.

Table 6: Output from first stage (monthly planning) - MOLP

Volume (tons)	**Product**	**From**	**To**
455	P2	F4	D1
300	P2	F4	D2
200	P1	F5	D1
320	P1	F5	D2

Table 7: Output from first stage (monthly planning) - LMOLP 1

Volume (tons)	**Product**	**From**	**To**
200	P1	F1	D1
320	P1	F2	D2
455	P2	F4	D1
300	P2	F4	D2

Table 8: Output from first stage (monthly planning) - LMOLP 2

Volume (tons)	Product	From	To
200	P1	F1	D1
320	P1	F2	D2
455	P2	F3	D1
300	P2	F3	D2

Regarding the minimization of distances between loading areas and destinations, the LMOLP 1 model presented the most favorable results, with the objective function equal to 94,640 (Table 7). The LMOLP2 model had the best result in terms of road quality, which was predictable since the priority of this model was to choose the best roads to use. The MOLP model presented the best result regarding the choice of landing areas that present timber that meets customer specifications according to the post-harvest time, prioritizing the choice of the timber near the due date for delivery. This is because in LMOLP models the timber post-harvest age was always the third factor to be minimized, while in MOLP it had the same weight as the other variables. The result of objective functions of the proposed models for the five forest, two products, and two destinations are presented in Table 9.

Table 9: Result of objective function of proposed models.

Objective functions	MOLP	LMOLP 1	LMOLP 2
Distance between timber pickup point and customer, weighted by timber volume (km) $\sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} \boldsymbol{d_{fe}}\, x_{fep}$	112,440	**94,640**	122,445
Roads quality (R1 = 1, and R2=2), weighted by timber volume $\sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} \boldsymbol{r_{f}}\, x_{fep}$	2,550	2,030	**1,275**
Timber days left to deliver, weighted by timber volume $\sum_{f=1}^{Nf}\sum_{e=1}^{Ne}\sum_{p=1}^{Np} \boldsymbol{a_{fp}}\, x_{fep}$	**48,265**	78,465	102,625

The costs from each solution technique can be seen in the Table 10. The LMOLP 1 model presented the lowest total cost, and the MOLP presented the highest. The average transport distance, which is the sum of the product of the distance and volume divided by total volume, was smaller in the LMOLP 1 model. Regarding the percentage of R1 (better quality roads), the LMOLP 2 model presented the highest percentage.

Table 10: Results of the three analyzed models.

	MOLP	LMOLP 1	LMOLP 2
Costs	$ 146,172.00	**$ 112,088.00**	$ 122,445.00
Average transport distance (tons/km)	88.19	**74.23**	90.04
Percentage R1	0%	50%	**100%**

3.2 Second stage of the decision process - weekly planning

The computational time was about 3 seconds for the second-phase decision model; it required 14 iterations. All truck trips required from a given loading area to a given destination were met with the proposed modeling. In the case study model, there were a total of 37 truck trips in a month, in order to achieve the requirement of a balance between the number of trips by truck per week, at least 8 truck trips per week must be made. The result of scheduling truck trips for timber transportation per week, proposed in the case study can be seen in Table 11.

Table 11: Result of truck trip scheduling per week

Pickup timber	**Scheduled trucks to destination 1**	**Scheduled trucks to destination 2**	**Total scheduled trucks**	
F4	8	0	8	Week 1
F4	4	0	8	Week 2
F4	0	4		
F4	4	0	8	Week 3
F1	0	4		
F1	1	0	9	Week 4
F2	0	8		

Table 12 shows the remaining days left to deliver timber for each trip truck each week. In week 1, the values of days left were lower than those presented in the following weeks, and so on, avoiding timber loss when delivering it within the established time.

Table 12: Days left to deliver timber per truck trip, per week.

	From	Scheduled trucks	Days left to deliver	To destination
Week 1	4	8	35	1
Week 2	4	4	35	1
	4	4	35	2
Week 3	4	4	35	1
	1	4	81	2
Week 4	1	1	81	1
	2	8	112	2

4 CONCLUSIONS

In this work, operational research tools were applied to support timber transportation planning based on the scenario observed in a large Brazilian forestry company, aiming to minimize costs. Different methods in multiple criteria problems are often used to generate a set of efficient solutions from which the decision-maker can choose. In Multi-objective optimization there is no general 'perfect' method that can address all situations, it is necessary to analyze each situation individually to make the decision.

4.1 The first stage of the decision process – the monthly planning

The lexicographic programming was flexible to solve a multi constraint problem. In this research, the Lexicographic Multi-Objective Linear Programming 1 (LMOLP 1) resulted in the lowest transportation cost, being 30% less than the cost resulting from the MOLP model, and 9% less than the LMOLP -2 model.

4.2 The second stage of the decision process – the weekly planning

The Lexicographic Goal Programming model for the weekly truck trips was highly suitable to solve weekly planning problem with complex multi attribute nature. It was produced a schedule that proved to be efficient, as all required truck trips were met, respecting each customer's requirement for post-harvest days, without any timber loss. The model written in Lindo software was efficient, but it presents the language although simple, very laborious, being difficult to notice errors in very large problems. More modern software, as CPLEX, with more efficient computational language is recommended to develop and solve large problems.

4.3 Model’s limitations and uncertainty

The quality of the acquisition and data collection, as well as actual and updated costs to feed the models, are fundamental for the reliability of the results. Unquantifiable factors and the model parametrizations for distance, roads, and freshness costs, although had worked well for the study case, could generate misleading solutions when analyzing a data set with different characteristics. In forest business, timber demands and stocks are dynamic, and there are many unforeseen situations, such as truck breakdown, road problems, strikes, and others; and to use the same model with no update can increases the chances of not getting the best possible result.

4.4 Recommendation and suggestions for future research

It is recommended to improve the models test it on larger dataset to determine its ability to solve these problems with larger conflicting data. In future studies, it is suggested to consider different types of trucks with different capacities, as well as the distances corresponding daily tours that include the time to travel to the garage, and the travel time of the unladen truck to account for the workload considering the labor laws. More constraints according to the actual challenges should be added to increase the reliability of the model.

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APPENDIX A

Appendix A: Input data - the monthly planning

- Study case – monthly planning 1

a) Stock of products (P1 and P2) in tons at forest landing areas 1, 2, 3, 4,and 5.

Stock (tons)	P1	P2
F1	6273.797	0
F2	1355.444	0
F3	0	5620.416
F4	0	6854.473
F5	11673.97	0

b) Distance between Forest and Destination

Distance	D1	D2
F1	56	96
F2	103	79
F3	123	100
F4	112	24
F5	65	129

c) Days left to deliver timber to customers requiring up to 150 days post harvested.

Days left to deliver		
	P1	**P2**
F1	81	0
F2	112	0
F3	0	67
F4	0	35
F5	42	0

d) Road quality

Road Quality	
F1	1
F2	1
F3	1
F4	2

e) Timber volume (tons) demand for product (P1 and P2) and destination (customer) (D1 and D2)

Demand	P1	P2
D1	200	455
D2	320	300

APPENDIX B

Appendix B: OPL Script to model MOLP

```
/*********************************************
 * OPL 12.8.0.0 Model
 * Author: Marinna Lopes
 * Contact: ml130@humboldt.edu
 * Creation Date: Oct 20, 2019 at 12:18:08 AM
 * Multi objective linear programming
 *********************************************/
// Variables

{string} Forest = ...;
{string} Products = ...;
{string} Destination = ...;


float Demand [Destination][Products]= ...; //volume in Kg
float Distance [Forest][Destination]= ...; //in Km
float Stock [Forest][Products]= ...; //volume in Kg
int Freshness [Forest][Products]=...; //Days left to transport timber
int Roads [Forest]=...; //roads quality


//Decision Variables
dvar float+ Delivered [Forest][Destination][Products];

//Objective Function
dexpr float Opt_Distance = sum (u in Forest, c in Destination, p in Products)
Distance[u][c] * Delivered[u][c][p];
dexpr float Opt_Freshness =  sum (u in Forest, c in Destination, p in
Products) Freshness[u][p] * Delivered[u][c][p];
dexpr float Opt_Roads =  sum (u in Forest, c in Destination, p in Products)
Roads[u] * Delivered[u][c][p];

minimize
Opt_Distance  + Opt_Freshness + Opt_Roads;

//Constraints
subject to {
forall (p in Products)
      forall (u in Forest)
            sum (c in Destination)
                  Delivered[u][c][p] <= Stock [u][p];

forall (p in Products)
```

```
	forall (c in Destination)
		sum (u in Forest)
			Delivered[u][c][p] >= Demand[c][p];
execute Output {
	writeln ("Delivered Plan")
		for (var u in Forest)
			for (var c in Destination)
				for (var p in Products)
					if (Delivered [u][c][p]>0) {
					writeln (Delivered [u][c][p] + '' + " tons
will be delivered from Forest " + '' + u + " of product " +''+ p + " to the
destination " +''+ c);
   }
}
```

```
/*********************************************
 * OPL 12.8.0.0 Data
 * Author: Marinna Lopes
 * Contact: ml130@humboldt.edu
 * Creation Date: Oct 20, 2019 at 11:05:18 PM
 * Data – Excel connection
 *********************************************/

// Variables

Forest = {"F 1","F 2","F 3","F 4","F 5"};
Products = {"P1","P2"};
Destination = {"D1","D2"};


SheetConnection sheet(" …. ");


Demand from SheetRead(sheet,"Demand");
Distance from SheetRead(sheet,"Distance");
Stock from SheetRead(sheet,"Stock");
Freshness from SheetRead(sheet,"Freshness");
Roads from SheetRead(sheet,"Roads");
```

APPENDIX C

Appendix C: OPL Script to model LMOLP 1

```
/*********************************************
 * OPL 12.8.0.0 Model
 * Author: Marinna Lopes
 * Contact: ml130@humboldt.edu
 * Creation Date: Oct 21, 2019 at 11:21:09 AM
 * Lexicographic multi objective linear programming
 * 1st: Distance, 2nd:Roads, 3rd: Freshness
 *********************************************/
using CP;

// Variables

{string} Forest = ...;
{string} Products = ...;
{string} Destination = ...;


float Demand [Destination][Products]= ...; //volume in Kg
float Distance [Forest][Destination]= ...; //in Km
float Stock [Forest][Products]= ...; //volume in Kg
int Freshness [Forest][Products]=...; //Days left to transport timber
int Roads [Forest]=...; //Roads quality


execute {
cp.param.timeLimit=60; // work for 60 segunds
}


//Decision Variables
dvar int+ Delivered [Forest][Destination][Products];

//Objective Function
dexpr float Opt_Distance = sum (u in Forest, c in Destination, p in Products)
Distance[u][c] * Delivered[u][c][p];
dexpr float Optimize_Roads = sum (u in Forest, c in Destination, p in
Products) Roads[u] * Delivered[u][c][p];
dexpr float Opt_Freshness =  sum (u in Forest, c in Destination, p in
Products) Freshness[u][p] * Delivered[u][c][p];

minimize staticLex (Opt_Distance,Optimize_Roads,Opt_Freshness);
```

```
//Constraints
subject to {
forall (p in Products)
	forall (u in Forest)
		sum (c in Destination)
			Delivered[u][c][p] <= Stock [u][p];

forall (p in Products)
	forall (c in Destination)
		sum (u in Forest)
			Delivered[u][c][p] >= Demand[c][p];
}

execute Output {
	writeln ("Delivered Plan")
		for (var u in Forest)
			for (var c in Destination)
				for (var p in Products)
					if (Delivered [u][c][p]>0) {
					writeln (Delivered [u][c][p] + '' + " tons
will be delivered from Forest " + '' + u + " of product " +''+ p + " to the
destination " +''+ c);
   }
}
```

```
/*********************************************
 * OPL 12.8.0.0 Data
 * Author: Marinna Lopes
 * Contact: ml130@humboldt.edu
 * Creation Date: Oct 20, 2019 at 11:05:18 PM
 * Data – Excel connection
 *********************************************/

// Variables

Forest = {"F 1","F 2","F 3","F 4","F 5"};
Products = {"P1","P2"};
Destination = {"D1","D2"};

SheetConnection sheet(" …. ");


Demand from SheetRead(sheet,"Demand");
Distance from SheetRead(sheet,"Distance");
Stock from SheetRead(sheet,"Stock");
Freshness from SheetRead(sheet,"Freshness");
Roads from SheetRead(sheet,"Roads"
```

APPENDIX D

Appendix D: OPL Script to model LMOLP 2

```
/*********************************************
 * OPL 12.8.0.0 Model
 * Author: Marinna Lopes
 * Contact: ml130@humboldt.edu
 * Creation Date: Oct 21, 2019 at 01:08:09 PM
 * Lexicographic multi objective linear programming 2
 *1st: Roads, 2nd:Distance, 3rd: Freshness
 *********************************************/
using CP;

// Variables

{string} Forest = ...;
{string} Products = ...;
{string} Destination = ...;


float Demand [Destination][Products]= ...; //volume in Kg
float Distance [Forest][Destination]= ...; //in Km
float Stock [Forest][Products]= ...; //volume in Kg
int Freshness [Forest][Products]=...; //Days left to transport timber
int Roads [Forest]=...; //Roads quality

execute {
cp.param.timeLimit=60; // parar em 1 min
}


//Decision Variables
dvar int+ Delivered [Forest][Destination][Products];

//Objective Function
dexpr float Optimize_Roads = sum (u in Forest, c in Destination, p in
Products) Roads[u] * Delivered[u][c][p];
dexpr float Opt_Distance = sum (u in Forest, c in Destination, p in Products)
Distance[u][c] * Delivered[u][c][p];
dexpr float Opt_Freshness =  sum (u in Forest, c in Destination, p in
Products) Freshness[u][p] * Delivered[u][c][p];

minimize staticLex (Optimize_Roads,Opt_Distance,Opt_Freshness);
```

```
//Constraints
subject to {
forall (p in Products)
	forall (u in Forest)
		sum (c in Destination)
			Delivered[u][c][p] <= Stock [u][p];

forall (p in Products)
	forall (c in Destination)
		sum (u in Forest)
			Delivered[u][c][p] >= Demand[c][p];
}


execute Output {
	writeln ("Delivered Plan")
		for (var u in Forest)
			for (var c in Destination)
				for (var p in Products)
					if (Delivered [u][c][p]>0) {
					writeln (Delivered [u][c][p] + '' + " tons
will be delivered from Forest " + '' + u + " of product " +''+ p + " to the
destination " +''+ c);
   }
}
```

```
/*********************************************
 * OPL 12.8.0.0 Data
 * Author: Marinna Lopes
 * Contact: ml130@humboldt.edu
 * Creation Date: Oct 20, 2019 at 11:05:18 PM
 * Data – Excel connection
 *********************************************/

// Variables

Forest = {"F 1","F 2","F 3","F 4","F 5"};
Products = {"P1","P2"};
Destination = {"D1","D2"};

SheetConnection sheet(" …. ");
```

```
Demand from SheetRead(sheet,"Demand");
Distance from SheetRead(sheet,"Distance"Stock from SheetRead(sheet,"Stock");
Freshness from SheetRead(sheet,"Freshness");
Roads from SheetRead(sheet,"Roads");
```

APPENDIX E

Appendix E: Script to model the weekly planning

Formulation in software LINDO version 6.1

```
Min p4

SUBJECT TO

p1=280
p2=280
p3=464


! Days left to timber delivered


1)81  X111 + 35 X411 + 112 X221 + 35 X421 - p1 = 0    !     Week  1
2)81  X112 + 35 X412 + 112 X222 + 35 X422 - p2 = 0    !     Week  2
3)81  X113 + 35 X413 + 112 X223 + 35 X423 - p3 = 0    !     Week  3
4)81  X114 + 35 X414 + 112 X224 + 35 X424 - p4 = 0    !     Week  4

! Number of trips truck from forest to destination in a month



5)     X111   +     X112   +     X113   +     X114   =     5

6)     X411   +     X412   +     X413   +     X414   =     12

7)     X221   +     X222   +     X223   +     X224   =     8

8)     X421   +     X422   +     X423   +     X424   =     8


!     Week  restriction
```

```
9)    X111  +    X411  +    X221  +    X421  >=8
10)   X112  +    X412  +    X222  +    X422  >=8
11)   X113  +    X413  +    X223  +    X423  >=8
12)   X114  +    X414  +    X224  +    X424  >=8

      END
```