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FORESTRY PLANNING

TESIS PARA OPTAR AL GRADO DE
DOCTOR EN SISTEMAS DE INGENIERÍA

CLAUDIO ENRIQUE PARADA VELIZ

PROFESOR GUÍA:
RAFAEL EPSTEIN NUMHAUSER

MIEMBROS DE LA COMISIÓN:
ANDRES WEINTRAUB POHORILLE
GUILLERMO DURAN

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RESUMEN DE LA MEMORIA PARA OPTAR
AL TÍTULO DE DOCTOR EN SISTEMAS DE INGENIERÍA
POR: CLAUDIO ENRIQUE PARADA VELIZ
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PROF. GUÍA: RAFAEL EPSTEIN NUMHAUSER

FORESTRY PLANNING

La industria forestal es una de las principales actividades económicas del país, por lo que el desarrollo de procesos de planificación forestal eficientes aparecen como una mejora significativa para su competetividad a nivel internacional.

La planificación forestal es una problemática de gran tamaño ya que requiere resolver problemas logísticos complejos, muchos de ellos de naturaleza combinatorial. Comenzando con resolver el problema de la red de caminos, la instalación de equipos de cosecha considerando la eficiencia de las maquinarias, predicción del crecimiento y rendimiento, definición de esquemas de trozado, y finalmente las decisiones que respectan al transporte. La mayoría de estos problemas son muy grandes y requieren de formulaciones con decisiones enteras y/o están relacionados con formulaciones matemáticas difíciles de resolver. Dado que estos problemas no han sido estudiados en profundidad para operaciones de gran escala económica, decidimos asumir el desafío de resolver dos de ellos con datos de operaciones reales.

En base a las estimaciones de largo plazo de carga potencial forestal para un transporte basado en trenes, definimos una matriz óptima de transporte.

También es muy importante estudiar la optimización de las operaciones forestales en terrenos con alta pendiente, las cuales son ejecutadas con sistemas de cables aéreos. Maximizar la carga útil de la operacición del cable es un factor relevante para mejorar los niveles de productividad forestal y alcanzar costos competitivos.

ABSTRACT OF THE DISSERTATION FOR THE
DEGREE OF DOCTOR EN SISTEMAS DE INGENIERÍA
AUTHOR: CLAUDIO ENRIQUE PARADA VELIZ
DATE: JANUARY 2020
THESIS ADVISER: RAFAEL EPSTEIN NUMHAUSER

FORESTRY PLANNING

Since forestry is one the main activities of the country, the development of efficient forestry planning processes appears as a significative improvement in its global competitiveness.

Forestry planning is a major challenge since it involves the solution of complex logistics problems most of them of combinatorial nature. Beginning with the road definition problems, followed by harvesting issues, such as machinery location and machine efficiency problems, yield-growth prediction and bucketing problems and ending with the set of transportation problems, most of them normally requires huge integer-based decision formulations and/or are related to mathematical formulations hard to solve. Since some of these problems have not been studied in deep under high-level of scale economics, we assume the challenge of solve two of them with real-life operational data.

Based on the long-term national estimation of the potential forestry load for railroad-based transportation systems, we define an optimal forestry transportation matrix.

It is also very important to study the optimization of steep terrain forestry operations, which are executed with cable logging systems. The maximization of cable yarding log payload is a relevant factor to improve forestry productivity levels and achieve competitive costs.

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Chapter 1

Study of railroad opportunities in the forestry sector transportation matrix

Abstract: *based on the long-term national estimation of the potential forestry load for railroad-based transportation systems, we defined a strategic transportation model for a big forestry company. The model defines transportation modes, required services, fleet structures and expected productivity and costs. As the model defines the long-term equilibrium for the associated transportation matrix, we used it to support a long-term railroad services bidding.*

1.1 Introduction

The present work looks for the opportunities to incorporate railroad freight to the transportation matrix for a Chilean forestry supply chain. It seeks to define required fleets, operational sizes, costs, associated operational savings and operational restrictions in a highly competitive truck transportation scenario with high levels of scale economics. To do so, we compare optimal truck transportation options against optimal railroad transportation options based on structure of operational costs.

Since the railroad infrastructure is not prepared to operate the forestry loading activities, such option will require important investments to activate suitable stations. This model based on high fixed costs would be feasible only under high levels of transportation.

Due to the uncertainties in potential long-term aggregate railroad demand, the Chilean national railroad company requested a strategic study which defined the potential demand for each one of the existing stations, defining the investments required in each one of them.

The literature related to the optimization of the forestry supply chain is extensive and has been studied by different authors over the last 20 years.

D'Amours et al. [11] indicates that there are numerous compilations available today in the literature that explore different perspectives on the forest supply chain. Röonqvist

[31], Martell et al. [28] and Epstein et al. [14] summarize the contribution of OR to the forest industry, focusing on various aspects related to forest production and transport to the forest products conversion industry. Carlsoon the al. [5] has focused on the planning and distribution of forest products to consumption centers. D'Amour's argues that there is a high relationship between the quality of forestry planning and operation and the performance of the supply chains of the different associated forest products, being reported by various researchers who have worked with aspects as diverse as forestry prescriptions, the sequencing of forest harvesting units, the construction of forest roads and the storage and transportation of forest products. In the Handbook on Operations Research in Natural Resources, Weintraub et al. [37] presents various models designed to improve the integrated planning of a forest production business.

Karlsson et al. [22] studies the problem of integrating the planning of operator crews, transportation and storage of forest products.

Karlsson et al. [23] has proposed a MIP model to solve the problem of forest harvesting, forest transport and road maintenance combined for a planning horizon of 1 year.

Forsberg et al. [16] has studied the integration of road transport with ship and rail transport for forest products. It defines the scope of logistics decisions in the strategic, tactical and operational field, focusing on strategic questions such as the need for a mixed transport matrix and tactical questions such as the capacities of train and truck fleets, the number and location of train-truck transfer stations in a bimodal transport system.

Mahmudi et al. [27] analyze the alternatives of direct biomass transport by truck versus bimodal transport, first by truck and then by train, concluding that the optimal combinations of transport by train and truck depend on the different supply distances.

Tahvanainen et al. [36] analyze the most efficient biomass transport systems for Finland according to the total transport distances, concluding that in distances over 135 kilometers, train transport is more competitive than truck transport.

In [29] Mathisen et al., highlight the greater energy efficiency of non-road freight transport systems over road transport, being the study of bimodal transport systems, via rail and sea systems for long distances, a critical action for the development of a sustainable transport system. According to this review, research on intermodal freight transport systems began to be developed in the early 1990s and from 2000 onwards there has been a steady increase in related publications that, according to the author, should be explained by the strong impulse of public policies to intermodal transport systems as a way to minimize the negative externalities of road transport systems. Despite the fact that the greater number of articles are related to rail transport in recent years there has been a growing interest in maritime transport although the author concludes that the analysis of the terminals is poorly developed.

In [9] Crainic et al. provides a frame of reference for the planning of intermodal transport systems, defining a 3-level taxonomy to classify the decisions associated with such a system, strategic or long-term for long-term investment decisions and which will determine the strategies of operation of the systems, including the design of the transport network, decisions of location of terminals, decision of purchase of equipment and tariff policies. The level of tactical decision seeks an efficient and rational allocation of existing resources in the system with the objective of improving its complete efficiency. These decisions are made at the aggregate level by abstracting detailed information. These decisions include the selection of the services to be performed, their optimal routes, general rules of operation of the terminals, product storage rules, traffic routing and repositioning of empty cars. Finally, the operational level is resolved locally and allows to organize the detailed activities of the vehicles and terminals, defining the sequencing of the services of loading, routing and dispatch of vehicles and the programming of the crews.

In [38], Wieberneit makes a review of published case studies of freight transport, mainly at a tactical level, whose resolution by exact methods is generally difficult to solve and describing the solution strategies used to solve these problems. In its conclusion, it states that many of these problems are still partially unsolved.

In [35], SteadieSeifi et al. makes a review of 2005 onwards developments and efforts in multimodal planning. His first conclusion is that there is an important effort in strategic and tactical planning but not at the operational levels. They also conclude that there are still important challenges in the area, such as in the study of the different transport network topologies to be defined, transport corridors, hubs and networks. Also, in the conflict between the objectives of minimizing costs and time, establishing the need to investigate multi-objective models for these trade-offs. According to the author, a very relevant challenge is to properly incorporate the planning of "back" flows in the planning of "outbound" flows by integrating the repositioning decisions of empty cars in the network design decisions. However, due to capacity constraints and those imposed by current legislation, it is necessary to incorporate multiple resources into the planning, for example, the joint planning of vehicles and drivers. Most publications assume that the transport system is centrally managed taking into account only the requirements of multimodal operations. Obviously, the interaction and competition between the different operators of the system influence the execution of the plan and their collaboration could be very beneficial in order to fulfill the plan. Moreover, the integration of different levels of planning could deliver more efficient solutions for the entire industry. However, the solution of each level separately is already a challenge given its high complexity. In this context, the use of relaxation and decomposition techniques and tools are used extensively. Branch cut algorithms deliver a flexible platform to include properties of network design problems, find stronger dimensions and cuts and increase limits on the sizes of solvable problems.

The paper is organized as follows: we first introduce the long terms national study of potential railroad load based on future stocks of wood plantations. We define potential transport of logs and transference node selection. Then, we present a specific logistic problem for a big Chilean forestry company. Based on previous work we define a forestry supply chain hierarchic planning model to use and their associated parameters. Finally, we introduce the bimodal supply chain model and current results and conclusions.

1.2 Long term national estimation

We estimate the potential railroad freight of forestry products for the next ten to fifteen years. The study is based on the localization of supply of logs and demands points as well as the available railway infrastructure and costs.

The methodology implemented considers the supply of most of the logs in the country, information supplied by the two main forestry companies in Chile, both providing long terms projections of flows of logs from origins to destinations for the next 20 years. Based on those flows and considering a valid truck-train transportation network it is feasible to build efficient alternative routes for each log flow, one being the direct truck travel from origin to client and the second one being a bimodal approach, namely modal truck-train transportation mode, which includes a first truck travel from the origin to an intermedia train station, a transference process from truck to train and a final train travel to the demand point. Then, and based on a unit cost model plus transference costs, it is possible to calculate the transportation cost for every feasible route of logs and select the most convenient option for any one of the flows.

The potential estimate of by-railroad demand of logs suppose a binary decision in every flow of logs since we assume a captive demand for the selected means of transport.

1.2.1 Chilean forestry industry background

The Chilean forestry industry relies on two basic areas, silvicultural operations and primary wood industry. The main products of the forestry industry are logs which are totally consumed by the national primary industry which in 2013 demanded 41 million of cubic meters. The national primary industry is composed mainly by cellulose mills, sawmills, industrial boards and plywood and chipping centers, as shown in Figure 1.1 (a big amount of the final products of this industry are exported).

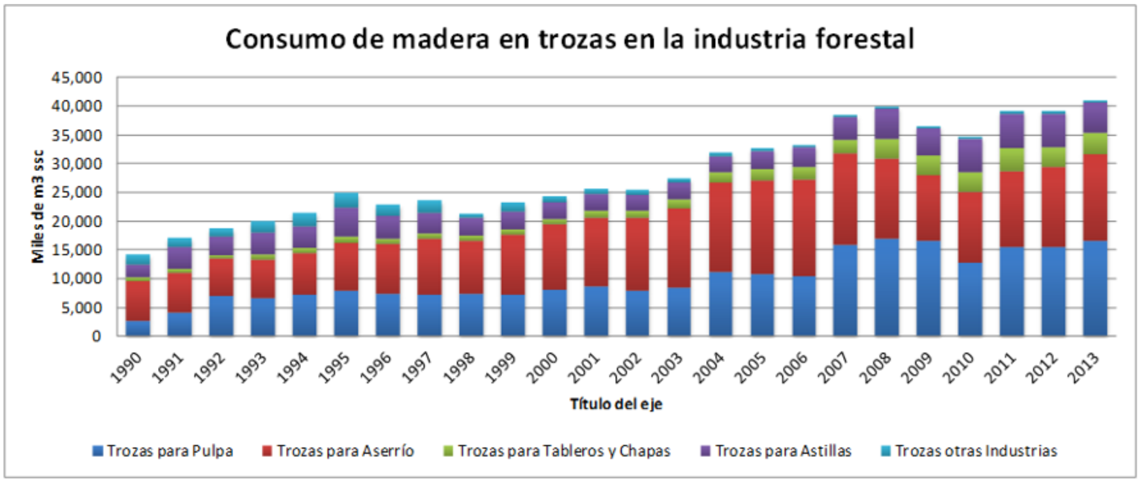


Figure 1.1: Historical industrial log consumption. Own elaboration. Source: INFOR report 2014.

Primary industry consumption

The industrial consumption has increased steadily beginning with 14 MM cubic meters by 1990 until 40 MM cubic meters in 2008. During 2009 the Chilean forestry sector was strongly affected by the Sub Prime Crisis reducing consumption by 8.7%. During 2010 the country was affected by a huge earthquake with big losses in the road and mill infrastructure. From 2011 and on the primary industry recovered the 2008th rates of consumption.

The cellulose industry is the main consumer of the country with a 40% of log's market share by 2013. There existed 11 Cellulose mills, 8 chemical kraft plants, the 3 remaining being mechanic mills and producing a total of 5 MM tons of cellulose by 2013. Ten of the eleven mills belong to the two main forestry companies.

Sawmills consumed 15 MM cubic meters by 2013, corresponding to the 37% of the log market. There existed 353 permanent sawmills producing a total of 7.7 MM cubic meters of solid wood in 2013. On that date, 51% of the sawmill production was concentrated in the biggest four forestry companies (Arauco, Cmpc, Forestal Tromen and Masisa), and nearly 35% of the sawmill production was exported.

The boards and plywood industry consumed 3.8 MM cubic meters by 2013, corresponding to the 9% of the log market and producing 2.67 MM cubic meters of panels. In 2012 a big forest fire destroyed Arauco's Nueva Aldea Plywood plant (440.000 cubic meters of annual production) rebuilt completely by 2014. Also, in 2013, Cmpc Plywood plant increased consumption by 500.000 cubic meters by year. By 2013, the 83% of the panels production was concentrated on the biggest 3 companies: Arauco, Cmpc and Masisa, and nearly 44% of the total production was exported.

The chipping industry consumed 5.2 MM cubic meters of logs by 2013, corresponding to the 12% of the log market. A little portion of the chipping process is done with eucalyptus in the forest to support the cellulose mill demand. There also exist chipping plants integrated to the sawmills processes which consumes waste from the sawmill process and elaborate chips for the cellulose industry. Those integrated plants consumed nearly 4.86 MM cubic meters of waste. Chips are raw material for the cellulose and chipboard industries but also to energy plants. The chipping industry produced 9,8 MM cubic meters of chips by 2013 and nearly 38% was exported. This market presented a high level of deconcentration with more than 42 chipping centers and 129 integrated chipping plants all from at least 25 different companies.

Finally, it is important to note that Arauco is building a new 5 MM cubic meters by year consumption cellulose mill (MAPA Project), mainly oriented to process eucalyptus and produce 2 MM tons by year of cellulose.

Stock of wood in plantations

INFOR (Chilean Forestry Data Institute) predicts future stocks of woods from plantations in the country. To do so, they solve a mathematical model to maximize the stock of wood for the three main species available (Radiata Pine, Eucalyptus Globulus and Eucalyptus

Nitens), satisfying minimal cutting ages and management of plantations restrictions to insure the sustainability of stock thru the years. Figure 1.2 shows the projection of volumes until 2040, and it is possible to appreciate that the available stock grows until 2019 and remains stable in 47 MM cubic meters until 2040, balanced with the installed and projected industry in the country.

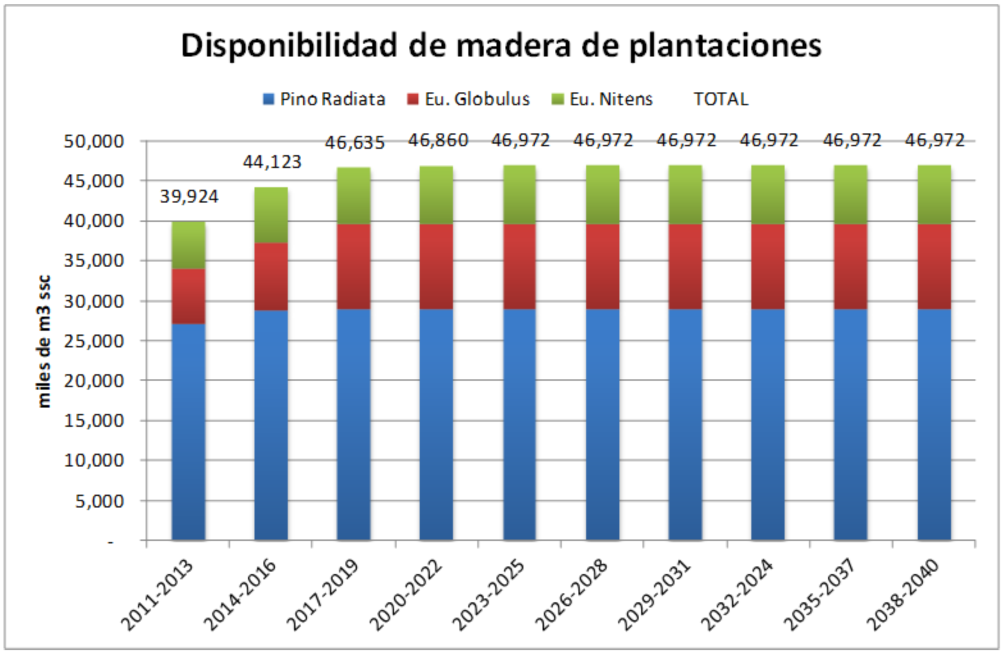


Figure 1.2: National availability of plantation future stocks. Source: INFOR, report 2014.

1.2.2 Log transport

The most common practice of transportation begins with logs just harvested stockpiled in landings or besides the road. Even when in some conditions the logs must be transported to intermedia courts, with a lot of extra management costs, most of the times the logs are transported directly to the final destinations.

In the special case of Radiata Pine timber products, since the length and width of the logs to transport is a commercial condition, there could be a previous packing process in order to optimize the container dimensions of the transport machinery.

Legal regulations allow a maximum weight of 45 tons for every truck loaded. Since a normal tare is about 15 tons, the maximum load per truck is 30 tons. For a long time, CORMA (Chilean national organization of timber producers) has been promoting an increase in the maximum weight of trucks to 60 tons. This new regulation would allow the use of B-Train, trucks with higher capacity and much lower logistics costs associated.

Of the 41 million of cubic meters transported in 2013, only 300 thousand were transported by train, less than 1% of the total.

Rail freight transport of forestry products is carried out completely in EFE railway network. EFE is the national railway company and own all the railway infrastructure. The transport service is executed by two private carrier companies, FEPASA and TRANSAP, both oriented to the forestry and Mining industries. Until 2013, the joint services of both companies reached 10.6 million of cubic meters by year. Figure 1.3 shows that the forestry participation of the carrier services during 2014 was 51%.

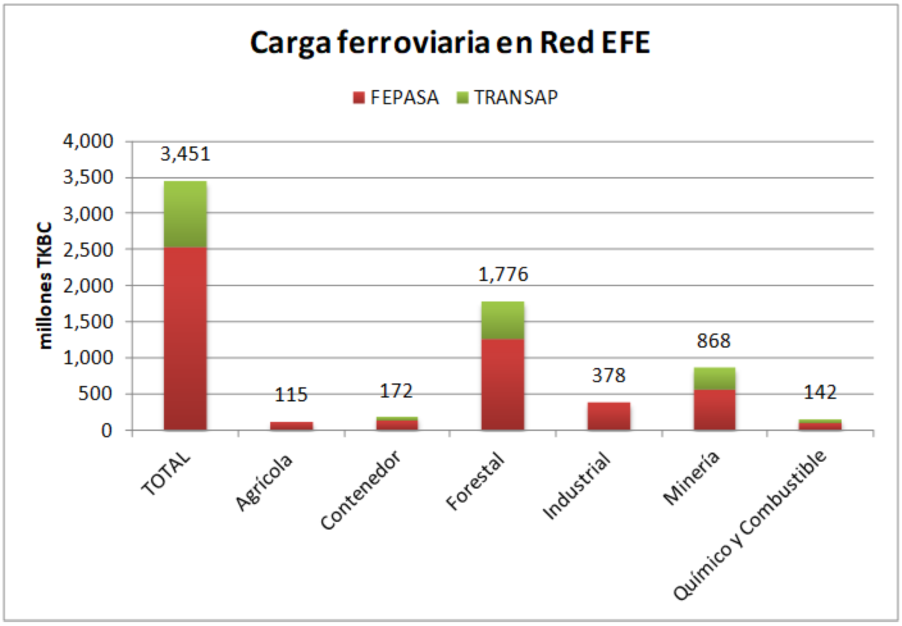


Figure 1.3: Railroad freight distribution over EFE network in year 2014.

Carrier companies are contracted by clients and by law EFE charges for the use of infrastructure in a mixed modality of fixed and variable tolls, the first one, the right to use of the infrastructure is a fixed charge, the second one, a fixed annual charge to use different sections of the railroad network and finally a variable charge for tons transported per kilometer.

This toll mode impose high barriers to the entry of new carriers since current ones already considers as sunken the fixed charges. The current law ends in 2024 and most potentials new carriers expect a more competitive system to open since then.

As an example of concentration of volumes in few carriers, Figure 1.4 shows the distribution of the 2013 FEPASA freight forestry volumes corresponding to 7.3 MM tons.

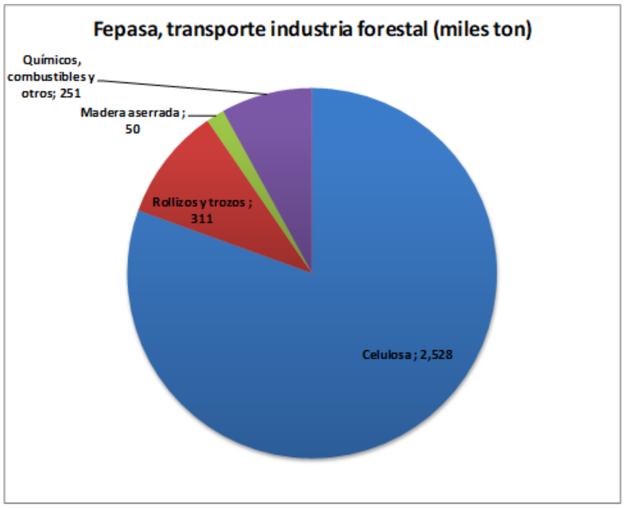


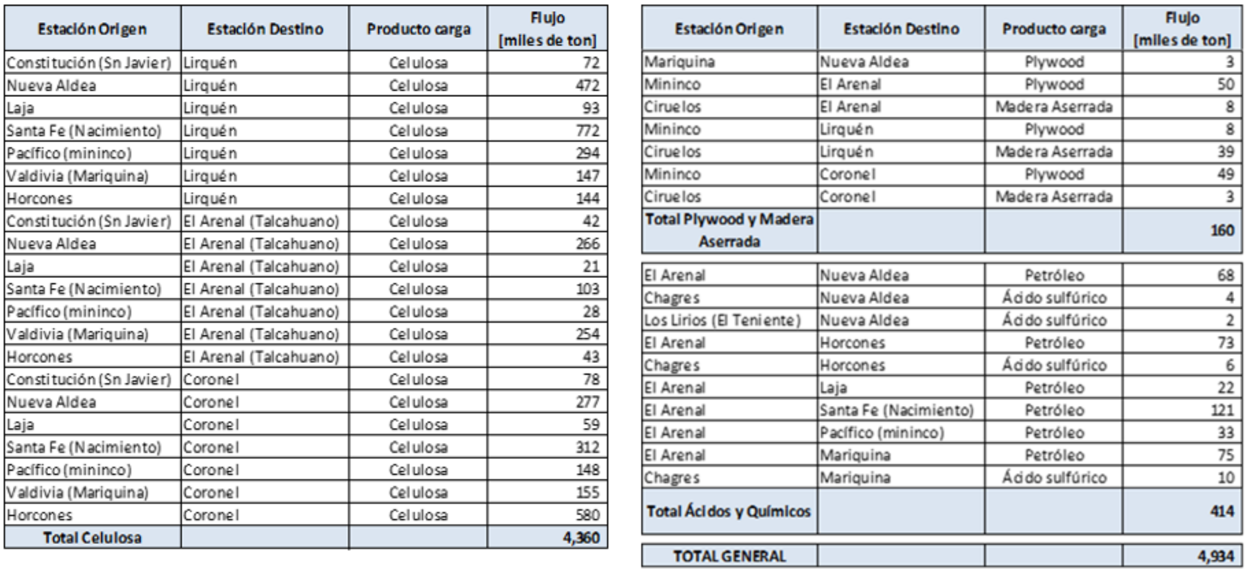
Figure 1.4: FEPASA forestry freight volume distribution year 2013.

Table 1.1 shows the volume of logs transported by train in 2014. The grand total of 365 thousand of tons is mainly composed by deliveries to mills Nueva Aldea and Nacimiento and El Arenal port. The average transportation distance was 213 kilometers and the minimal transportation distance was 128 kilometers.

Estación Origen	Estación Destino	Flujo [miles de ton]	Distancia Recorrida [Km]	miles de Ton-Km
Molina	Nacimiento	10	344	3,438
Escuadron	Nueva Aldea	10	195	1,946
Horcones	Nueva Aldea	131	227	29,685
Inspector Fernandez	Nueva Aldea	63	226	14,213
Inspector Fernandez	Lirquen	2	211	422
Inspector Fernandez	Horcones	6	244	1,466
Inspector Fernandez	Mariquina	39	185	7,203
Lautaro	Arenal	5	246	1,230
Lautaro	Nacimiento	61	128	7,826
Pillanlelbun	Arenal	25	259	6,473
Pitrufquen	Nueva Aldea	1	325	325
Pitrufquen	Arenal	12	305	3,654
Total		**365**	**2,894**	**77,881**
Promedio		**30**	**213**	**6,490**

Table 1.1: Log flow associated to train transportation, year 2014. Source: EFE.

Table 1.2 shows other forestry products transported by train in 2014. Of the approximate 5 MM tons, the main products were cellulose (88%), cellulose supplies (8%) and plywood (3%).



Estación Origen	Estación Destino	Producto carga	Flujo [miles de ton]
Constitución (Sn Javier)	Lirquén	Celulosa	72
Nueva Aldea	Lirquén	Celulosa	472
Laja	Lirquén	Celulosa	93
Santa Fe (Nacimiento)	Lirquén	Celulosa	772
Pacífico (mininco)	Lirquén	Celulosa	294
Valdivia (Mariquina)	Lirquén	Celulosa	147
Horcones	Lirquén	Celulosa	144
Constitución (Sn Javier)	El Arenal (Talcahuano)	Celulosa	42
Nueva Aldea	El Arenal (Talcahuano)	Celulosa	266
Laja	El Arenal (Talcahuano)	Celulosa	21
Santa Fe (Nacimiento)	El Arenal (Talcahuano)	Celulosa	103
Pacífico (mininco)	El Arenal (Talcahuano)	Celulosa	28
Valdivia (Mariquina)	El Arenal (Talcahuano)	Celulosa	254
Horcones	El Arenal (Talcahuano)	Celulosa	43
Constitución (Sn Javier)	Coronel	Celulosa	78
Nueva Aldea	Coronel	Celulosa	277
Laja	Coronel	Celulosa	59
Santa Fe (Nacimiento)	Coronel	Celulosa	312
Pacífico (mininco)	Coronel	Celulosa	148
Valdivia (Mariquina)	Coronel	Celulosa	155
Horcones	Coronel	Celulosa	580
Total Celulosa			**4,360**

Estación Origen	Estación Destino	Producto carga	Flujo [miles de ton]
Mariquina	Nueva Aldea	Plywood	3
Mininco	El Arenal	Plywood	50
Ciruelos	El Arenal	Madera Aserrada	8
Mininco	Lirquén	Plywood	8
Ciruelos	Lirquén	Madera Aserrada	39
Mininco	Coronel	Plywood	49
Ciruelos	Coronel	Madera Aserrada	3
Total Plywood y Madera Aserrada			**160**
El Arenal	Nueva Aldea	Petróleo	68
Chagres	Nueva Aldea	Ácido sulfúrico	4
Los Lirios (El Teniente)	Nueva Aldea	Ácido sulfúrico	2
El Arenal	Horcones	Petróleo	73
Chagres	Horcones	Ácido sulfúrico	6
El Arenal	Laja	Petróleo	22
El Arenal	Santa Fe (Nacimiento)	Petróleo	121
El Arenal	Pacífico (mininco)	Petróleo	33
El Arenal	Mariquina	Petróleo	75
Chagres	Mariquina	Ácido sulfúrico	10
Total Ácidos y Químicos			**414**
TOTAL GENERAL			**4,934**

Table 1.2: Forestry product flow (different than logs) by train, year 2014. Source: EFE report.

1.2.3 Basic information

There is detailed information on the two mail forestry companies of the country.

The basic information consists of the flow of logs from the origins to the consumption centers in a yearly basis. Each company provides long term projections with volumes harvested in each forestry origin every year identifying species and products. As the forestry business is a long term one and since the areas planted in the current year must be harvested in between 10 and 15 years, in case of Eucalyptus, or in between 18 and 26 years in case of Radiata Pine, strategic long term forestry planning process must consider at least 30 years horizons using growth simulation models to estimate the final performance of each forest. Both companies use optimality models to forecast the future flows.

There are also Geographic Information System (G.I.S.) data of EFE railroad network. The study will consider the southern section of the network beginning in the north of the country in Rancagua station (Libertador Bernardo O'Higgins Region) and finishing in "La Paloma" station (Los Lagos Region). Figure 1.6 shows the railroad network section used in the study. There is also detailed information of the national road network including primary and secondary roads, as shown in Figure 1.5.

As a criterion to determine if a consumption center is accessible to the railroad network, we defined that it would be connected (or would be easily connected) to the actual railroad network. To do so, we defined a parameter of 5 kilometers of maximum distance between them. Figure 1.7 shows the main consumption centers of the country.

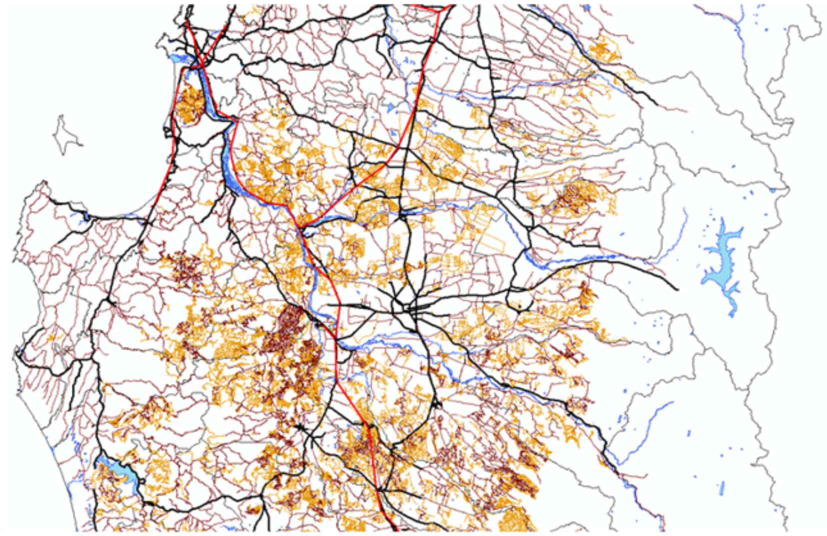


Figure 1.5: Section of National road network used in present study.

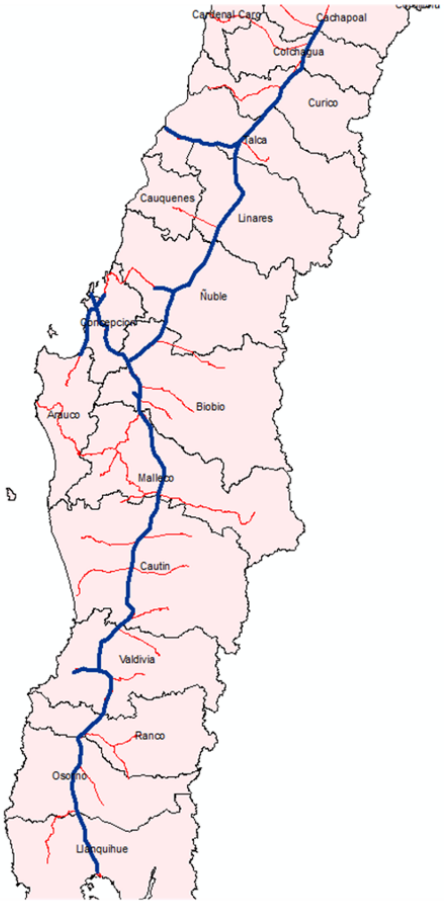


Figure 1.6: EFE railroad used in the present study. In blue active railroad. Own Elaboration.

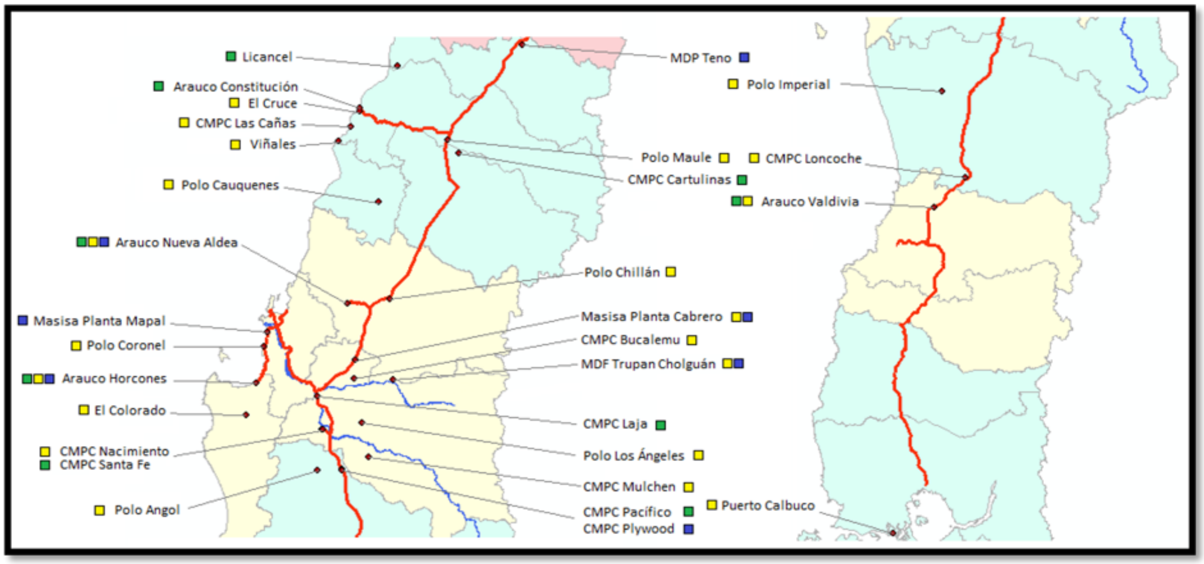


Figure 1.7: Geographic localization of main consumption centers: Arauco, CMPC y MASISA.

1.2.4 Methodology

Firstly, for each origin and destination tuple we define two potential roads, one directly by truck and the other using transference from truck to train. To do so, we used an own developed computer system1 which evaluates all feasible routes over the complete railroad plus road networks and obtain efficient routes for both cases based on an "equivalent kilometer" index.

In second term, we calculate the associated cost for each pair of routes, based on unitary costs for truck and train transportation (US$/ton-kilometer) plus a transference bimodal cost (US$/ton). For the case of truck transportation cost, it is necessary to add a toll cost which is already considered in the case of train costs. Finally, we choose the cheapest option for each tuple origin and destination.

The train freight demand estimation considers a binary modal decision. Contrary to the passenger transportation demand estimation, in which the binary modal decision must be done thru a discrete choice model based on random utility theory, In the case of freight transportation, it is assumed that the demand is captive of the best option for the producer (we assume the unit of demand as the flow defined in between each origin and destination).

The demand information is available as the estimation of annual flow from origin to destination for the two main companies of the country, corresponding to the 70% of the national production, considering the production in own lands plus the trade of logs with thirds parties. This market share will increase with the launch of MAPA project and Arauco's new sawmill by 2022.

As we assume as potential train destination the closer one to existing railroads (less than 5 kilometers), these will require few investments to be connected to the railroad. From the existing destinations, Loncoche sawmill and Nacimiento cellulose mill must be connected to the railroad.

In relation to the trade logs, both companies privilege the purchase of logs near the mills, looking for minimal transportation costs, which make trading logs unattractive for train transportation.

The modal truck-train option considers a transference operation in a site next to the actual stations as a way to perform such operations in an efficient way. These operations include the discharge of trucks, the loads of train cars and the stock piling of logs. The base scenario will allow to use any station as transference node and would possibly activate a bigger amount of transference nodes than the strictly necessary. Section I.2.6 studies the minimal amount of necessary transference nodes and the impacts in train logs availability.

Route development

To elaborate all the feasible origin to destination routes for the model, both truck and truck-train modal routes, we develop a routing system based on all valid train and truck connections in between origins and destinations. The system provides efficient routes to connect two points of the network based on equivalent-kilometer indexes, which amplified kilometers in dirty and graveled roads thru a conversion factor1. The system evaluates truck and truck-train routes and select the best based on minimal equivalent-kilometer indexes.

Cost model and modal selection

Figure 1.8 shows the cost model applied to the selection of the route for every origin to destination flow.

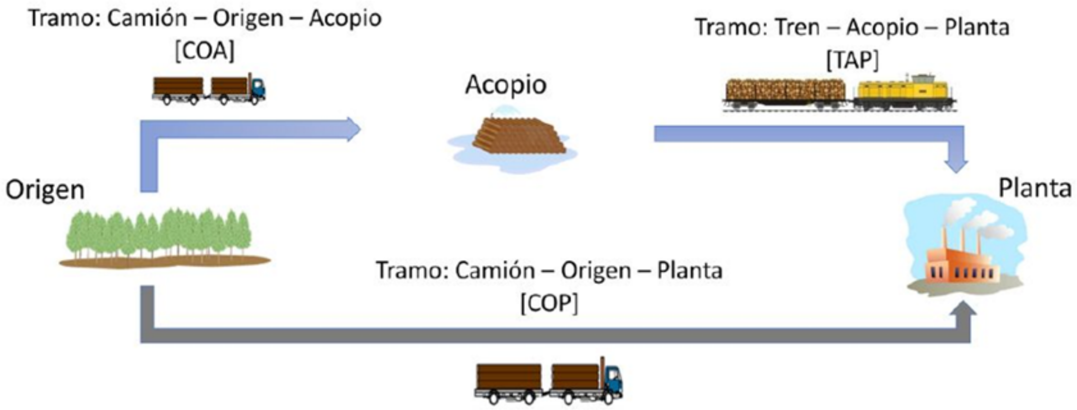


Figure 1.8: Cost Model applied to both transportation modes. Source: Own Elaboration.

The parameters used in the model are:

CtoTteCam:	The cost of moving a ton of logs for one kilometer by truck
CtoDesCam:	The cost of unload a ton of logs by truck
CtoCarCam:	The cost of load a ton of logs by truck
CtoTteTren:	The cost of moving a ton of logs for one kilometer by train
CtoDesTren:	The cost of unload a ton of logs by train
CtoCarTren:	The cost of load a ton of logs by train
CtoCancha:	The incurred cost to keep a ton of logs in a transference node

As we can observe in Figure 1.8, the by-truck route needs only one load operation in the origin and one unload operation in the destination while the bimodal truck-train route includes an extra load plus unload operations in transference node. If we assume similar load/unload costs for truck and train, the main difference in between the two options occurs in the transference node. We can define the parameter CtoAcop as the combined load/unload cost for the operation of a ton of logs in a transference node in US$/ton.

CtoAcop: CtoDesCam + CtoCarTren + CtoCancha

Then, the equations required to compare both routes are:

Truck Cost= CtoTteCam * DistCOP [US$/Ton]
Train Cost= (CtoTteCam * DistCOA + CtoAcop + CtoTteTren * DistTAP) [US$/Ton]

We define Truck Cost as the logistic value of transfer 1 Ton of Logs using route COP.

We define Train Cost as the logistic value of transfer 1 Ton of Logs using firstly the route COA, then passing by the transference node and finally using the route TAP.

In some of the road segments used in both routes it is necessary to include a toll value which may be relevant to decide the cheaper option. Figure 1.9 shows the toll applied to specific roads and therefore included in corresponding routes.

Figure 1.9: Toll map. Own Elaboration.

1.2.5 Base scenario results

The log density factor, which defines the weight of logs in tons derived from cubic meters depends on a series of factors including the moist content and the shape of the logs.

We are using factor 0.910 (cubic meters/Ton) obtained from a 2010 Valdivia mill study (Vera1). This value agrees with FAO UNECE studies (including 13 Europe countries plus US) which defines values in between 0.912 and 0.8941.

The marginal transportation cost by truck (US$/ton_kilometer) used in this study is made up of the transportation cost from origin to destination, which depends on the road materials, paved roads, gravel roads, dirt roads and so on, but also depends on the fixed costs of timeouts of trucks in origins and destinations. As the timeout cost is modelled fixed, the marginal cost of a short route became marginally more expensive than a longer route.

The average transportation cost by truck for routes over 50 kilometers is 0.08 [US$/ton_kilometer] and 0.068 [US$/ton_equivalent_kilometer].

As mentioned previously, the transportation cost model by truck is based on an "equivalent kilometer" concept (the consideration of no-paved road surface kilometers been amplified in terms of the paved/unpaved truck speed relationship) which enables to use a cost formula based only in term of paved road surfaces. We use the value 2.3 as the Paved/unpaved speed relationship.

The previous calculus of average transportation cost for trucks considers only routes over 50 kilometers since shorter routes are unattractive for train services.

This calculus does not consider the use of toll in concession roads since the toll values are applied to forestry transportation cost in a route by route basis as shown by Figure I 9.

The average train transportation cost considered in the study is 0.038 [US$/ton_kilometer].

We validate this number based on 2013 FEPASA Annual Report which indicates an average cost of 0.034 US$/ton_equivalent_kilometer. The 76% of the total FEPASA flow consists of cellulose shipping. As the log density is much lower than the cellulose one, the 10% of over cost is consistent with these cost parameters.

The value 0.038 [US$/ton_kilometer] represent the value of transportation services that carriers charge forestry companies and do not represent carriers cost structure.

A correct comparison of by-truck and by-train transportation cost requires to consider toll charges in concession roads. Table 1.3 shows the toll charges considered.

Ruta 5 Sur	Quinta	US$ 11.08
	Río Claro	US$ 11.08
	Retiro	US$ 11.08
	Santa Clara	US$ 11.54
	Las Maicas	US$ 11.54
	Pua	US$ 10.92
	Quepe	US$ 10.92
Autopista del Itata	Agua Amarilla	US$ 17.45
	Rafael	US$ 8.67
Ruta 160	Chivilingo	US$ 13.38
	Curanilahue	US$ 11.15
	Pilpilco	US$ 11.15
Ruta 148	Chaimávida	US$ 4.46
Ruta 156	San Roque	US$ 7.69

Table 1.3: Comparison by-truck and by-train transportation costs.

As mentioned earlier, the study considers a by-train transportation model including nodes to execute truck to train logs transference services. These services include log unload/load operations. To estimate the transference node unit cost we consolidate service values from the two main forestry companies and obtained a value of US$ 2.92, which considers temporary storage of logs in the transference node.

In order to define suitable transference nodes, it is important to consider their log transference rate. Section 1.2.6 shows a 25 transference nodes scenario which defines a 154 thousand m3/year average flow for each transference node and a 30 transference nodes scenario which defines a 137 thousand m3/year flow for each node.

With a 150 thousand m3/year net flow of logs and considering 44 shift/month (11 shifts by week, working in double shit from Monday to Friday plus an extra shift in Saturdays) it will be necessary to serve 10 trucks by shift. A loader machine can manage this flow of logs efficiently.

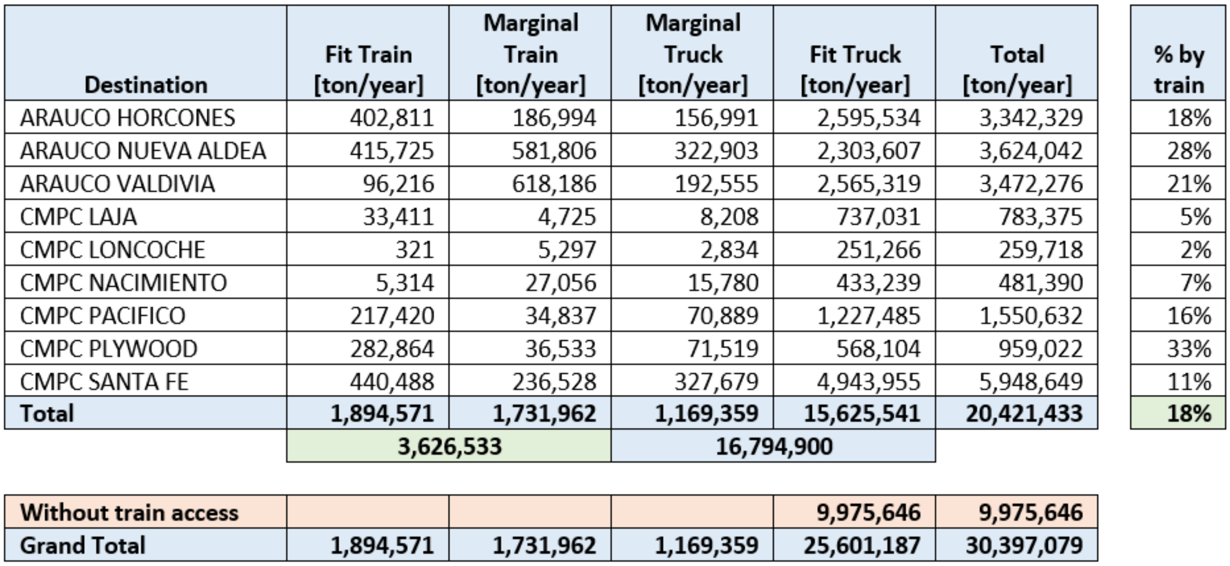
Flow of logs modal selection

In order to have a better understanding of the convenience of the modal decision (truck against modal truck-train transportation mode) we define the following classification of flows:

- Fit Truck: Truck route is more than 10% cheaper than truck-train route
- Marginal Truck: Truck route is less than 10% cheaper than truck-train route
- Marginal Train: Truck-train route is less than 10% cheaper than truck route
- Fit Train: Truck-train route is more than 10% cheaper than truck route

By using the above classification, it is possible to appreciate the modal selections of flows of logs sensitive to change in parameter values, meaning "marginal flows", and modal selections of flows of logs insensitive to change in parameter values, meaning "Fit flows".

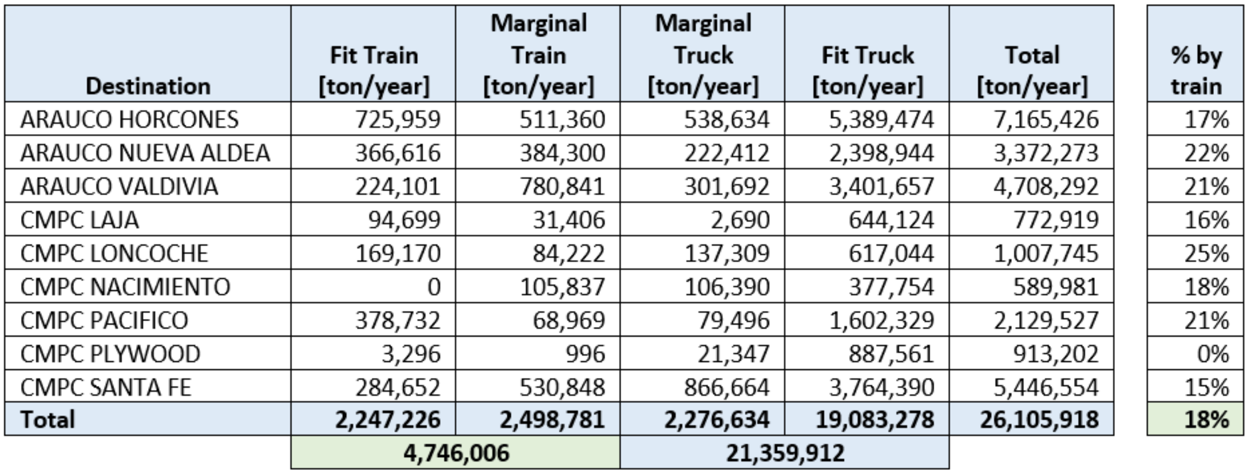
The primary result indicates that in the period 2016 to 2019, an average of 3.6 MM m3/year are economically convenient to transport by truck-train modal operations. Of these, about 1.9 MM m3/year are convenient by less than a 10% of the cost.



Destination	Fit Train [ton/year]	Marginal Train [ton/year]	Marginal Truck [ton/year]	Fit Truck [ton/year]	Total [ton/year]	% by train
ARAUCO HORCONES	402,811	186,994	156,991	2,595,534	3,342,329	18%
ARAUCO NUEVA ALDEA	415,725	581,806	322,903	2,303,607	3,624,042	28%
ARAUCO VALDIVIA	96,216	618,186	192,555	2,565,319	3,472,276	21%
CMPC LAJA	33,411	4,725	8,208	737,031	783,375	5%
CMPC LONCOCHE	321	5,297	2,834	251,266	259,718	2%
CMPC NACIMIENTO	5,314	27,056	15,780	433,239	481,390	7%
CMPC PACIFICO	217,420	34,837	70,889	1,227,485	1,550,632	16%
CMPC PLYWOOD	282,864	36,533	71,519	568,104	959,022	33%
CMPC SANTA FE	440,488	236,528	327,679	4,943,955	5,948,649	11%
Total	**1,894,571**	**1,731,962**	**1,169,359**	**15,625,541**	**20,421,433**	**18%**
	3,626,533		**16,794,900**			
Without train access				**9,975,646**	**9,975,646**	
Grand Total	**1,894,571**	**1,731,962**	**1,169,359**	**25,601,187**	**30,397,079**	

Table 1.4: Annual average flow in period 2016 - 2019.

In the period 2020 to 2023, an average of 4.7 MM m3/year are economically convenient to transport by truck-train modal operations. Of these, about 2.2 MM m3/year are convenient by less than a 10% of the cost. Table 1.4 and Table 1.5 shows these results classified by destination.



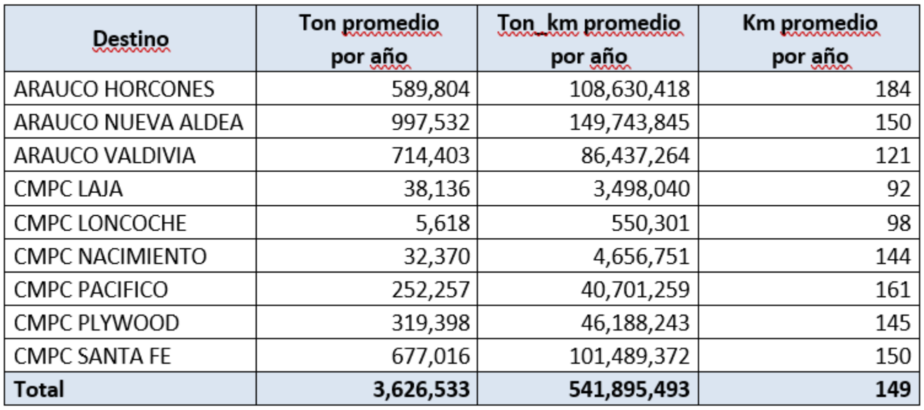
Destination	Fit Train [ton/year]	Marginal Train [ton/year]	Marginal Truck [ton/year]	Fit Truck [ton/year]	Total [ton/year]	% by train
ARAUCO HORCONES	725,959	511,360	538,634	5,389,474	7,165,426	17%
ARAUCO NUEVA ALDEA	366,616	384,300	222,412	2,398,944	3,372,273	22%
ARAUCO VALDIVIA	224,101	780,841	301,692	3,401,657	4,708,292	21%
CMPC LAJA	94,699	31,406	2,690	644,124	772,919	16%
CMPC LONCOCHE	169,170	84,222	137,309	617,044	1,007,745	25%
CMPC NACIMIENTO	0	105,837	106,390	377,754	589,981	18%
CMPC PACIFICO	378,732	68,969	79,496	1,602,329	2,129,527	21%
CMPC PLYWOOD	3,296	996	21,347	887,561	913,202	0%
CMPC SANTA FE	284,652	530,848	866,664	3,764,390	5,446,554	15%
Total	**2,247,226**	**2,498,781**	**2,276,634**	**19,083,278**	**26,105,918**	**18%**
	4,746,006		**21,359,912**			

Table 1.5: Annual average flow in period 2020 - 2023.

The long terms plantation stocks predictions indicate a stable behavior of log flows from 2024 onwards.

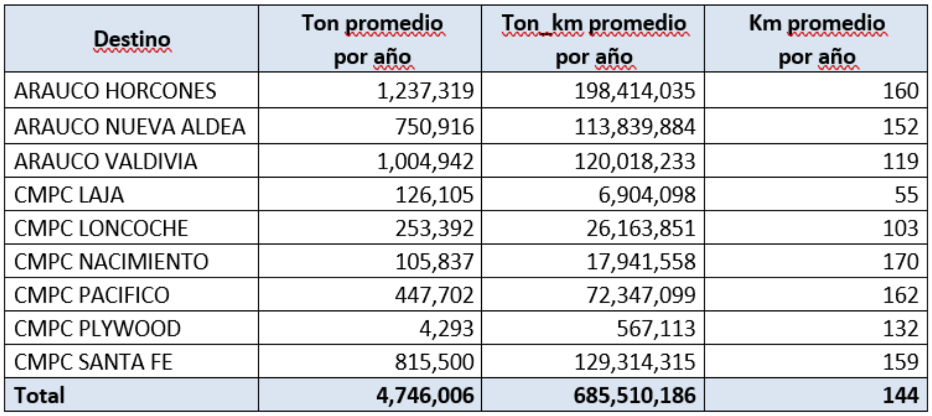
The volume of logs to be purchased to third parties is classified as “Fit Truck” since it will be mainly transported from locations near to mills that are inconvenient for train operations.

The launch of Arauco’s main Project (MAPA) explain the increase of flow in 2020. Based on available information, there are no evidence of further relevant projects nor the increase of the annual availability of plantation timber until 2040. Table 1.6 and Table 1.7 characterizes the flows by train classified by destination for periods 2016 to 2019 and 2020 to 2023. It shows average tons by year, average tons_kilometers by year and average train distance by year.



Destino	Ton promedio por año	Ton_km promedio por año	Km promedio por año
ARAUCO HORCONES	589,804	108,630,418	184
ARAUCO NUEVA ALDEA	997,532	149,743,845	150
ARAUCO VALDIVIA	714,403	86,437,264	121
CMPC LAJA	38,136	3,498,040	92
CMPC LONCOCHE	5,618	550,301	98
CMPC NACIMIENTO	32,370	4,656,751	144
CMPC PACIFICO	252,257	40,701,259	161
CMPC PLYWOOD	319,398	46,188,243	145
CMPC SANTA FE	677,016	101,489,372	150
Total	**3,626,533**	**541,895,493**	**149**

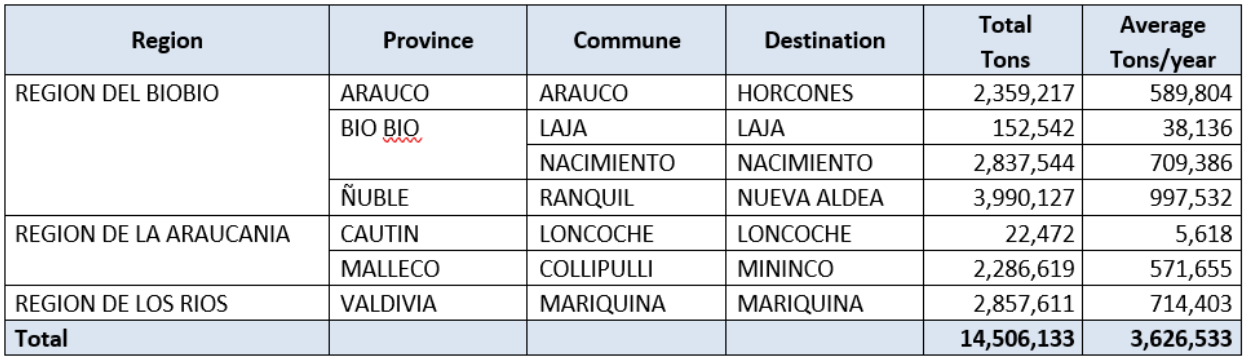
Table 1.6: By-train transportation mode flows for period 2016 - 2019.



Destino	Ton promedio por año	Ton_km promedio por año	Km promedio por año
ARAUCO HORCONES	1,237,319	198,414,035	160
ARAUCO NUEVA ALDEA	750,916	113,839,884	152
ARAUCO VALDIVIA	1,004,942	120,018,233	119
CMPC LAJA	126,105	6,904,098	55
CMPC LONCOCHE	253,392	26,163,851	103
CMPC NACIMIENTO	105,837	17,941,558	170
CMPC PACIFICO	447,702	72,347,099	162
CMPC PLYWOOD	4,293	567,113	132
CMPC SANTA FE	815,500	129,314,315	159
Total	**4,746,006**	**685,510,186**	**144**

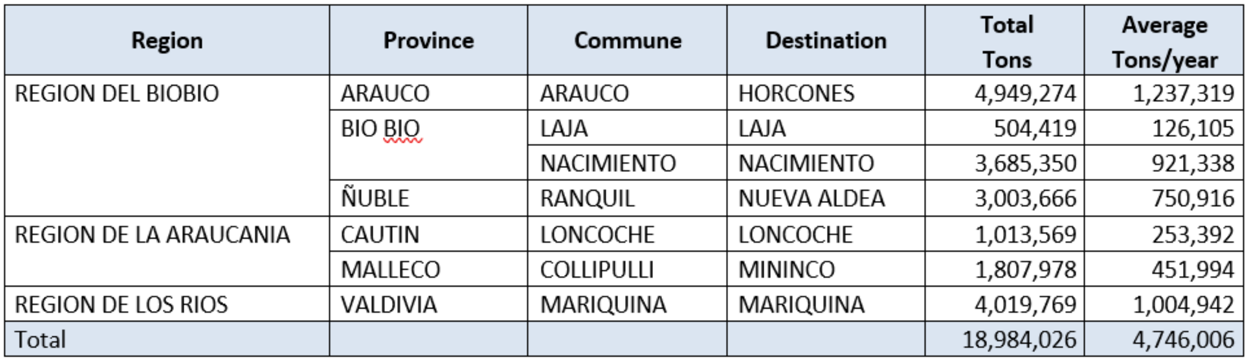
Table 1.7: By-train transportation mode flows for period 2020 - 2023.

Table 1.8 and Table 1.9 shows the log flow by train classified by destination for periods 2016 to 2019 and 2020 to 2023.



Region	Province	Commune	Destination	Total Tons	Average Tons/year
REGION DEL BIOBIO	ARAUCO	ARAUCO	HORCONES	2,359,217	589,804
	BIO BIO	LAJA	LAJA	152,542	38,136
		NACIMIENTO	NACIMIENTO	2,837,544	709,386
	ÑUBLE	RANQUIL	NUEVA ALDEA	3,990,127	997,532
REGION DE LA ARAUCANIA	CAUTIN	LONCOCHE	LONCOCHE	22,472	5,618
	MALLECO	COLLIPULLI	MININCO	2,286,619	571,655
REGION DE LOS RIOS	VALDIVIA	MARIQUINA	MARIQUINA	2,857,611	714,403
Total				**14,506,133**	**3,626,533**

Table 1.8: By-train transportation mode flows classified by destination for period 2016 - 2019.



Region	Province	Commune	Destination	Total Tons	Average Tons/year
REGION DEL BIOBIO	ARAUCO	ARAUCO	HORCONES	4,949,274	1,237,319
	BIO BIO	LAJA	LAJA	504,419	126,105
		NACIMIENTO	NACIMIENTO	3,685,350	921,338
	ÑUBLE	RANQUIL	NUEVA ALDEA	3,003,666	750,916
REGION DE LA ARAUCANIA	CAUTIN	LONCOCHE	LONCOCHE	1,013,569	253,392
	MALLECO	COLLIPULLI	MININCO	1,807,978	451,994
REGION DE LOS RIOS	VALDIVIA	MARIQUINA	MARIQUINA	4,019,769	1,004,942
Total				18,984,026	4,746,006

Table 1.9: By-train transportation mode flows classified by destination for period 2020 - 2023.

In period 2016 to 2019 the model activates 55 transference nodes, all of them related to one existing train station. The average logs flow is 86 M tons/year/node been Parral station the biggest one with a flow of 865 M tons/year. Since there are many nodes with minimal amounts of flow, we can concentrate the flow of logs in less stations, reducing the quantity of transference nodes required. Section 1.2.6 studies the convenience of deactivate different transference nodes and its impacts in the log flows by train.

From year 2020 onwards the model assigns an average of 4.7 MM m3/year by truck-train modal transportation system with an average index of 685 MM ton_kilometers. These results are significant compared with 365 M ton/year and 3.6 MM ton_kilometers of total log freight by 2014 and compared with a global freight amount of 10.6 MM ton/year and 1.7 MM ton_kilometers transported by EFE in 2013.

1.2.6 Transference nodes analysis

This section analyzes and defines the quantity and location of transference nodes required. The transference nodes are required for the modal truck-train transportation mode and involve an associated cost of transference activities which is relevant to decide the optimal transportation option for the flow. It is important to study the amount and location of transference nodes and its relationship with the total flow of logs convenient to the modal truck-train mode.

The transference nodes proposed for modal operations must be located adjacent to railroads. Without loss of generality we assume that transference node locations are neighbors to all existing train stations. We want to study the relationship in between the number of transference nodes and the availability of logs flows for modal truck-train transportation mode. The analysis is focused in the availability of different transference nodes, in which case, having lower availability of transference nodes, the truck approach trip from the forest to the transference node is longer and affects the selection of transportation mode decision. If we assume an equivalent land value along the railroad, the distance in between the transference node and the railroad station became irrelevant and we can consider the transference node adjacent to the train station.

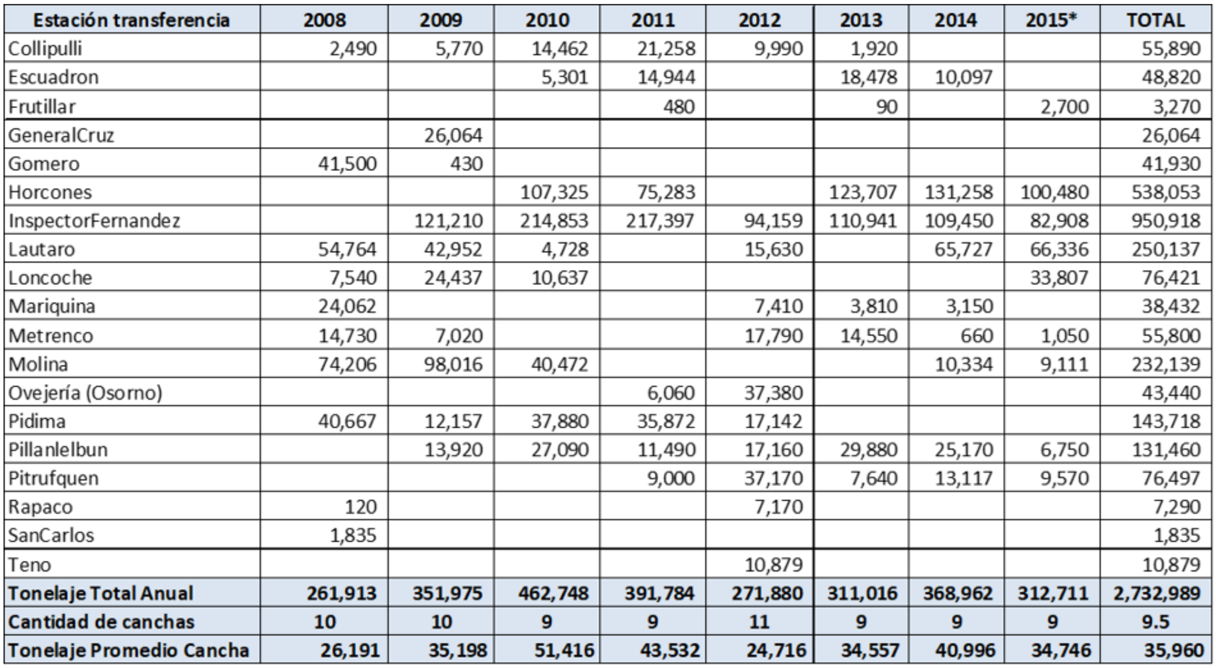
In contrast to the last definition, as the economic impact of the required transference node investments should be relevant for the modal truck-train transport mode final cost, which make of primal importance to minimize them and also it will be relevant to look for a location that minimize potential community conflicts, and since both conditions tends to move away transfer nodes from train stations then we must evaluate an optimal location for transference node as a trade off in between transference operations simplicity against investment considerations and community complexity.

Under the supposition of transference nodes adjacent to any existing train station the model uses 70 transference nodes from a potential of 112 transference nodes but many of them with low levels of logs flow.

This section shows the results of different scenarios, starting with 70 active transference nodes, and applying successive restrictions on the total number of active transference nodes to see the effect on the amount of log flows selected for the modal truck-train transport mode. This section is split into four parts: the transference nodes historically used, the node selection methodology, the definition of a node selection model and the results.

Transference nodes historically used

A transference node analysis starting point for the next decades should be the transference nodes used in the last years. Table 1.10 shows the log flows transferred in the period in between 2008 and 2015 in 19 different nodes with an annual average of 10 nodes used by year. Transference nodes are temporary facilities that may be activated in different years depending on the proximity of forestry activities. The average annual log flow is 36 M tons/year with a maximum of 217 M ton/year in node Inspector Fernandez.



Estación transferencia	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015***	**TOTAL**
Collipulli	2,490	5,770	14,462	21,258	9,990	1,920			55,890
Escuadron			5,301	14,944		18,478	10,097		48,820
Frutillar				480		90		2,700	3,270
GeneralCruz		26,064							26,064
Gomero	41,500	430							41,930
Horcones			107,325	75,283		123,707	131,258	100,480	538,053
InspectorFernandez		121,210	214,853	217,397	94,159	110,941	109,450	82,908	950,918
Lautaro	54,764	42,952	4,728		15,630		65,727	66,336	250,137
Loncoche	7,540	24,437	10,637					33,807	76,421
Mariquina	24,062				7,410	3,810	3,150		38,432
Metrenco	14,730	7,020			17,790	14,550	660	1,050	55,800
Molina	74,206	98,016	40,472				10,334	9,111	232,139
Ovejería (Osorno)				6,060	37,380				43,440
Pidima	40,667	12,157	37,880	35,872	17,142				143,718
Pillanlelbun		13,920	27,090	11,490	17,160	29,880	25,170	6,750	131,460
Pitrufquen				9,000	37,170	7,640	13,117	9,570	76,497
Rapaco	120				7,170				7,290
SanCarlos	1,835								1,835
Teno					10,879				10,879
Tonelaje Total Anual	**261,913**	**351,975**	**462,748**	**391,784**	**271,880**	**311,016**	**368,962**	**312,711**	**2,732,989**
Cantidad de canchas	**10**	**10**	**9**	**9**	**11**	**9**	**9**	**9**	**9.5**
Tonelaje Promedio Cancha	**26,191**	**35,198**	**51,416**	**43,532**	**24,716**	**34,557**	**40,996**	**34,746**	**35,960**

Table 1.10: Transference nodes historically used and annual flows (ton/year).

Node selection methodology

As mentioned previously, the base scenario assumed any transference node adjacent to an existing train station as activated, resulting in 70 active transference nodes (see Table 1.11). This would be the "free scenario" in which scale economics are not considered due to the concentration of log flows in a reduced number of transference nodes. The following scenarios are being obtained by closing successively potential transference nodes and analyzing impacts over log flow selection for the modal truck-train transport mode.

Due the big amount of train stations (and subsequently potential transference nodes) we decided to close 10 transference nodes in every iteration (exceptionally in the last iteration we closed just 5 nodes).

Station	Esc. 70 transf. Nodes ton/year
CHIMBARONGO	11,106
QUINTA	13,820
CURICO	1,574
LONTUE	35,651
CAMARICO	13,720
PANGUILEMU	14,810
TALCA	126
MAULE	4,789
SAN JAVIER	133,828
VILLA ALEGRE	6,573
LINARES	194,105
MIRAFLORES	2,129
LONGAVI	61,637
PARRAL	294,024
NIQUEN	35,403
COCHARCAS	16,545
CHILLAN	25,775
NEBUCO	1,529
BULNES	21,151
GENERAL CRUZ	12,234
CABRERO	27,790
MONTE AGUILA	8,502
YUMBEL	5,234
TURQUIA	15,576
SAN ROSENDO	616
BUENURAQUI	3,875
GOMERO	2,888
UNIHUE	1,542
QUILACOYA	50,822
HUALQUI	202,179
CHIGUAYANTE	9,588
CONCEPCION	6,682
LIRQUEN	160,081
LOMAS COLORADAS	2,341
ESCUADRON	41,515

Station	Esc. 70 transf. nodes ton/year
HORCONES	335,086
LAJA	16,205
DIUQUIN	2
SANTA FE	87,145
RENAICO	155,294
MININCO	1,663
COLLIPULLI	54,427
PIDIMA	1,481
ERCILLA	14,685
INSPECTOR FERNANDEZ	161
VICTORIA	185,968
PUA	4,798
LAUTARO	298,535
CAJON	56,817
TEMUCO	215,796
METRENCO	79,765
FREIRE	265,540
PITRUFQUEN	14,857
GORBEA	43,565
LASTARRIA	31,554
LONCOCHE	106,517
LANCO	34,886
MARIQUINA	21,042
MAFIL	5,081
VALDIVIA	18,281
LOS LAGOS	13,881
REUMEN	52
PAILLACO	5,526
RAPACO	149,109
LA UNION	266,137
CARACOL	26,665
OSORNO	141,968
RIO NEGRO	71,624
PURRANQUE	14,476
CORTE ALTO	7,921

Table 1.11: Transference nodes used in Base Scenario. Period 2016 - 2023.

In order to deactivate transference nodes, we assume that associated log flows would be redistributed to another active transference node. The deactivation criterion considers that additional movement of logs to other transference nodes is minimized. Namely, we choose 10 stations to deactivate under the assumption of minimal additional movement in ton_kilometers to redistribute log flows associated, what is achieved by closing nodes with less flow and near to others.

Given the big amount of potential “deactivation node” combinations we build a MIP model to select the required nodes to close.

Definition of a node selection model

The proposed MIP looks for the minimization of log movement (measured in ton_kilometers) when we redistribute the flow of deactivated nodes. The mathematical model associated is described below:

Sets

e, j	Transference node initially active

Parameters

$Flow_\mathrm{e}$	Initial flow associated to transference node e
$Dist_{\mathrm{e}j}$	Railway distance in between transference nodes e and j
N	Quantity of transference nodes that will be deactivated

Variables

Y_e	Binary variable Y is set to 1 when transference node e will be deactivated, otherwise 0
$X_{\mathrm{e}j}$	Proportion of flow from deactivated transference node e that will be redistributed to node j

Equations

Objective function

Minimize the extra movement of logs (in ton_kilometers) when deactivating N transference nodes. The flow of logs initially assigned to these N nodes will be redistributed to other activated nodes with an additional freight movement.

$$FO = \sum_{\mathrm{e},j} Flow_\mathrm{e} * Dist_{\mathrm{e}j} * X_{\mathrm{e}j}$$

Out-Flow Node e Conservation

The in-flow of logs initially assigned to deactivated node e must be completely redistributed to activate nodes j.

$$\sum_{j} X_{j\mathrm{e}} = Y_\mathrm{e} \forall Flow_\mathrm{e} > 0$$

In-flow Node e Conservation

The in-flow of logs redistributed to node e must be 0 when is deactivated, otherwise may receive flow from deactivated nodes j.

$$\sum_{j} X_{j\mathrm{e}} <= N * (1 - Y_{\mathrm{e}} \forall Flow_{\mathrm{e}} > 0$$

Total quantity of deactivated nodes

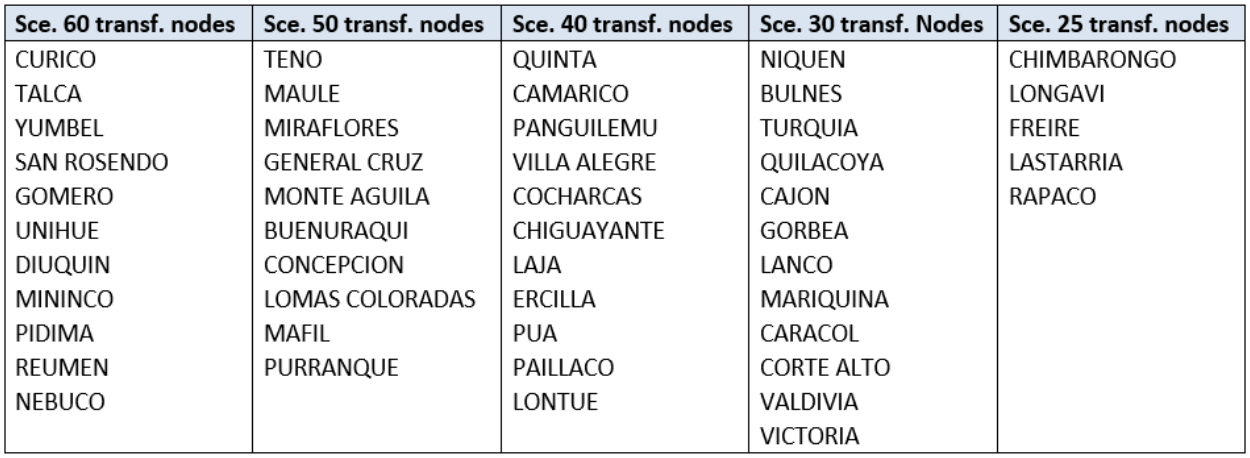
The summary of Y variables must be equal to the quantity of nodes to deactivate (N).

$$\sum_{\mathrm{e}} Y_{\mathrm{e}} = N$$

Results

Starting with the “free scenario” in which there were 70 activated transference nodes we defined 5 additional scenarios by iteratively deactivate 10 transference nodes from the previous scenario, with exception on the last scenario in which we deactivate only 5 nodes. As a way to simplify nomenclature we will refer to each scenario as the number of active nodes, by example “70 nodes scenario” will be the basic “free scenario”.

We use the same transport mode selection procedure as in the base scenario described in Section 1.2.4 using the routing system for each origin-destination flow of logs we selected the most convenient truck route and the most convenient modal truck-train route and then selected the cheapest one. Since the best truck route will be always the same, every time we deactivated transference nodes, we updated the routing system and calculated again the best modal truck-train route and selected the cheapest one in between the two transportation modes. Table 1.12 shows the transference nodes deactivated in each of the five iterations of the model. It is important to note that there are more than 10 deactivated nodes in some iterations, and it is explained by the presence of previous unused transference nodes that are activated in the current iteration. These new nodes are incorporated to the active set of active nodes, deactivating previous active ones.



Sce. 60 transf. nodes	Sce. 50 transf. nodes	Sce. 40 transf. nodes	Sce. 30 transf. Nodes	Sce. 25 transf. nodes
CURICO	TENO	QUINTA	NIQUEN	CHIMBARONGO
TALCA	MAULE	CAMARICO	BULNES	LONGAVI
YUMBEL	MIRAFLORES	PANGUILEMU	TURQUIA	FREIRE
SAN ROSENDO	GENERAL CRUZ	VILLA ALEGRE	QUILACOYA	LASTARRIA
GOMERO	MONTE AGUILA	COCHARCAS	CAJON	RAPACO
UNIHUE	BUENURAQUI	CHIGUAYANTE	GORBEA	
DIUQUIN	CONCEPCION	LAJA	LANCO	
MININCO	LOMAS COLORADAS	ERCILLA	MARIQUINA	
PIDIMA	MAFIL	PUA	CARACOL	
REUMEN	PURRANQUE	PAILLACO	CORTE ALTO	
NEBUCO		LONTUE	VALDIVIA	
			VICTORIA	

Table 1.12: Incrementally deactivated transference nodes.

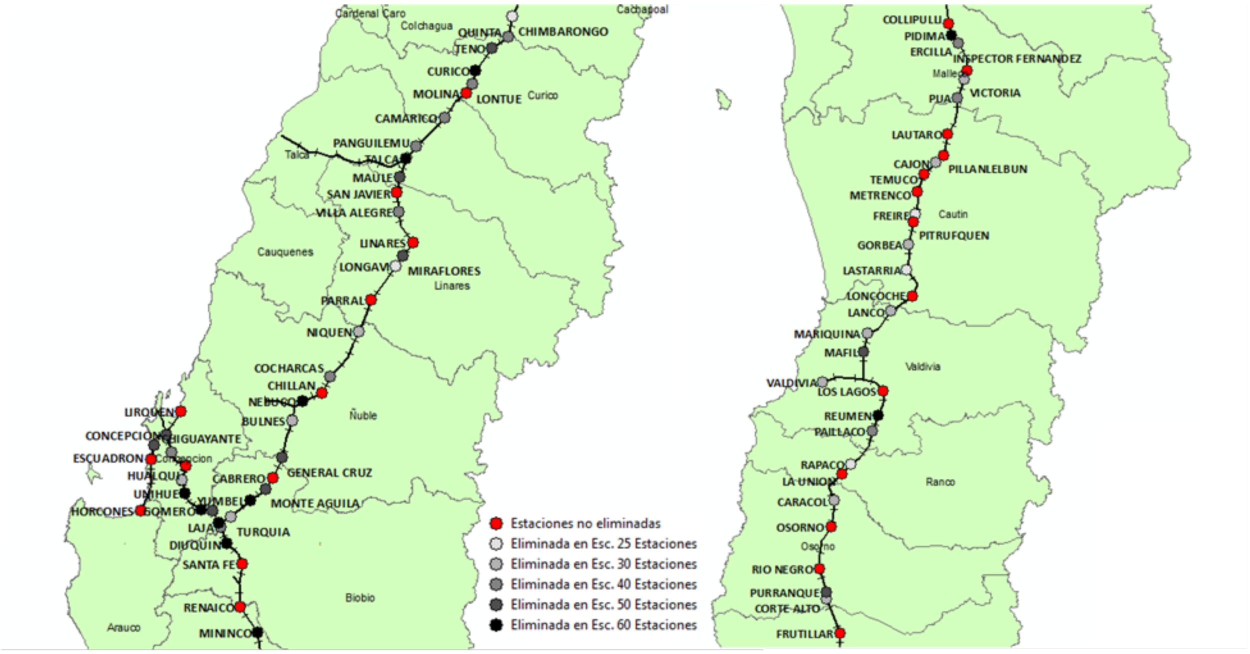


Figure 1.10: Transference nodes selection process scheme.

Figure 1.10 shows the selected transference nodes in each iteration.

The next example will help us to appreciate the effect of deactivating transference nodes. Figure 1.11 shows the flow of logs from Pencahue commune to the south of the country. Initially the modal truck-train transportation mode used a truck route connecting to the railroad in “Talca” transference node. In the first iteration “60 nodes scenario”, the model deactivates the transference node “Talca” and must use the transference node named “Maule” to connect the modal truck-train transport mode, which is further from the origin than “Talca” and considers a longer truck trip and a shorter train trip. This new route is less competitive than the previous one.

Even when at the first iterations the process of deactivating transference nodes may have marginal effects since there are many transference nodes and very close to each other, the next iterations will decrease the amount of log flows selected to be carried by modal truck-train transportation mode.

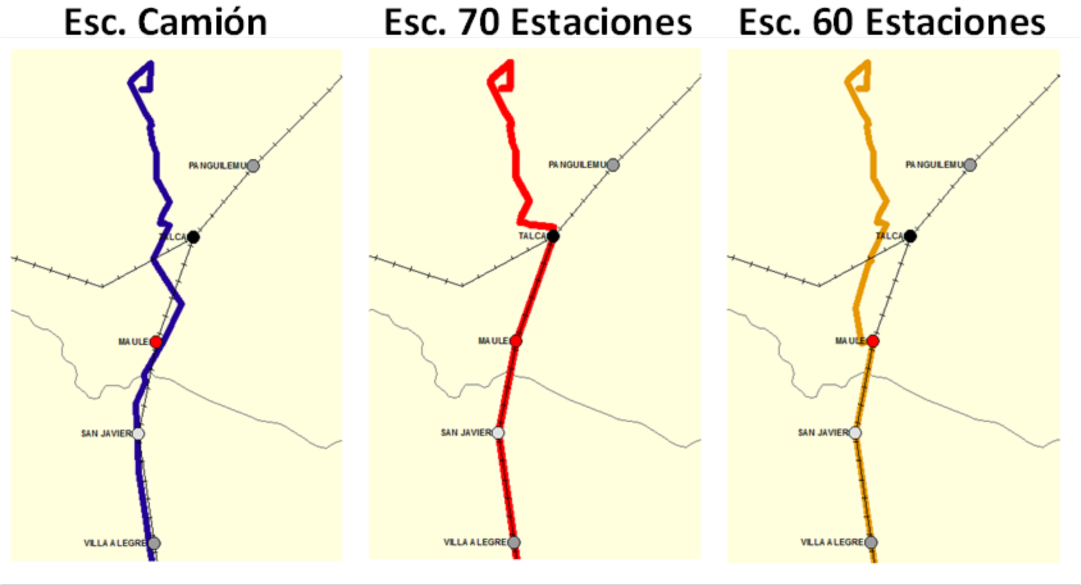


Figure 1.11: Example of truck-train transportation mode change of selected transference nodes.

Table 1.13 compares the 6 scenarios in terms of total tons/year carried by modal truck-train transportation mode.

Scenario	Avg. 2016 - 2019	Avg. 2020 - 2023	Average	Cumulative decrease	Cumulative Decrease	Tons. of deactivated nodes
	[ton/year]	[ton/year]	[ton/year]	[ton/year]	[%]	[ton/year]
70 nodes	3,626,533	4,746,006	4,186,270	0	0%	0
60 nodes	3,622,643	4,746,006	4,184,325	1,945	0%	16,708
50 nodes	3,609,890	4,743,321	4,176,606	9,664	0%	69,558
40 nodes	3,588,284	4,727,359	4,157,821	28,449	1%	161,038
30 nodes	3,538,218	4,679,361	4,108,789	77,480	2%	554,730
25 nodes	3,273,205	4,436,042	3,854,624	331,646	8%	575,261

Table 1.13: Incremental decrease of flow selected to modal truck-train transportation mode.

The last column shows the average of tons/year associated to the deactivated transference nodes in each iteration. This value indicates the total amount of flow that may pass to the truck transportation mode, but some of it will be associated to other transference nodes. The column "accumulated decrease" shows the flow that effectively pass from modal to truck transportation mode. When passing from iteration “30 nodes scenario” to the iteration “25 nodes scenario” the amount of flow in “risk” to change of transportation mode is 575 M tons/year but only 254 M tons/year change their transportation mode.

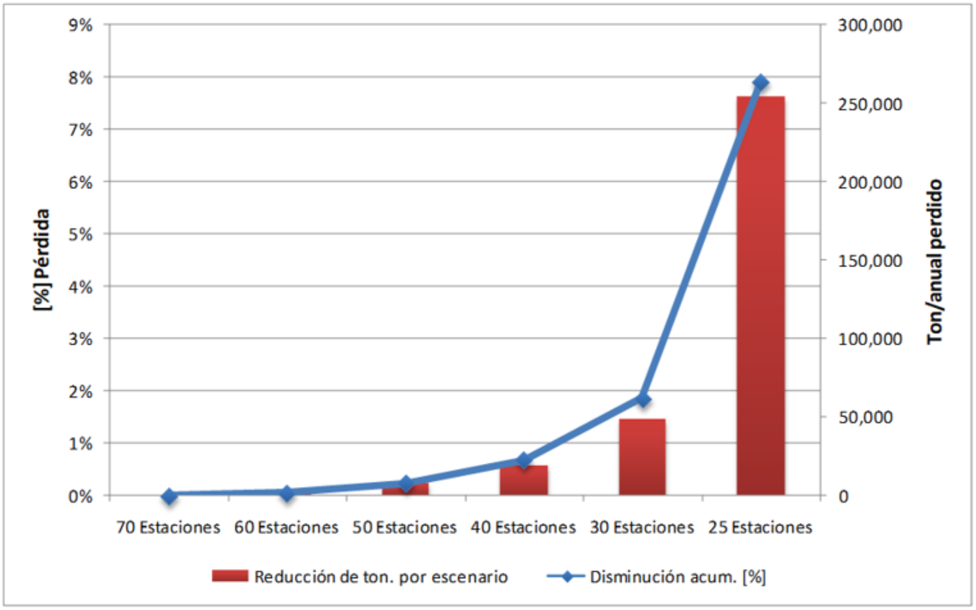


Figure 1.12: Accumulated decrease of Flow assigned to modal truck-train transportation mode.

Figure 1.12 shows the amount of flow passed from modal to truck transportation mode and the percentage of flow loss from modal transportation mode. As the model has initially many transference nodes activated, decreasing them do not affect the amount of flow carried by the modal transportation mode. The “30 nodes scenario” report a loss less than 2%. However, the “25 nodes scenario” reports a loss of 8% and, given the exponential shape of the % of loss curve, we can infer a big impact with fewer active transference nodes.

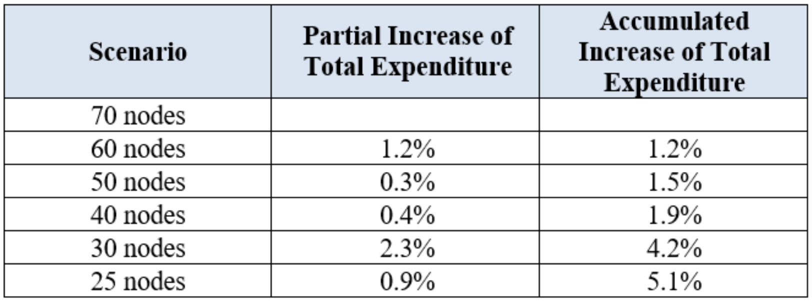
A second look at the decrease of active transference nodes would be to analyze flows measured in ton_kilometers. Table 1.14 shows the flows in terms of equivalent ton-kilometers, summarized from annual averages for the period in between 2016 and 2023, in which we consider for each flow from origin to destination only the cheapest transportation mode.

Scenario	Mix Routes Train Section	Mix Routes Complete Route	Truck Routes Complete Route	Route both modes Complete route	Dif. Both Modes Complete Route
70 nodes	613,702,839	871,268,481	1,340,713,780	2,211,982,261	0
60 nodes	613,571,000	870,955,397	1,378,046,983	2,249,002,380	37,020,119
50 nodes	612,797,723	870,355,900	1,385,843,714	2,256,199,614	7,197,234
40 nodes	609,865,726	868,598,114	1,391,683,924	2,260,282,039	4,082,425
30 nodes	604,945,094	867,681,093	1,474,520,404	2,342,201,496	81,919,457
25 nodes	576,028,808	813,666,093	1,534,962,684	2,348,628,777	6,427,281

Table 1.14: Flow tons-kilometer-equivalent selection of cheapest mode (Annual Average, Period 2016 -2023).

It is possible to infer a decrease of modal transportation mode selection directly related with the decrease of active transference nodes. Additionally, there is an inverse relationship in between the average travel distance of the total transportation system and the number of active transference nodes.

Finally, the amount of variation of the total expenditure in transportation is presented in Table 1.15, with little impact in first iterations, but with a 4% increase in the "30 nodes scenario" compared with a 2% of modal transportation loss and a 5% increase of expense compared with an 8% of modal transportation loss.



Scenario	Partial Increase of Total Expenditure	Accumulated Increase of Total Expenditure
70 nodes		
60 nodes	1.2%	1.2%
50 nodes	0.3%	1.5%
40 nodes	0.4%	1.9%
30 nodes	2.3%	4.2%
25 nodes	0.9%	5.1%

Table 1.15: Expenses increase in transportation caused by decrease of activated nodes (period 2016-2023).

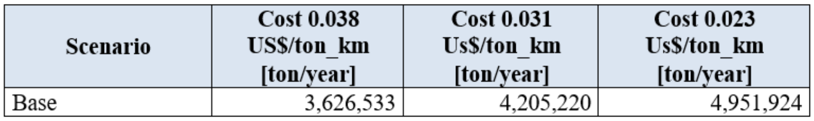
1.2.7 Transportation cost scenario

This section is oriented to a sensitivity analysis on transportation cost parameters and its impacts over the flow of log carried out by modal transportation mode. This sensitivity is referred to market changes or variations in costs and supplies and technology or infrastructure improvements in transportation services.

It is important to note that the selection of transportation mode for log flows depend on the relative relationship of both transportation mode parameters so that a proportional change in parameters from both transportation modes will not change the current decision. So, we decide to perform a sensibility analysis based only on changes of modal transportation parameters.

The referential cost of train transportation used in the model is 0.038 US$/ton_kilometer. The sensibility analysis considers two scenarios over train transportation cost variations of 0.031 US$/ton_kilometer and 0.023 US$/ton_kilometer.

Table 1.16 and Figure 1.13 shows for the period in between 2016 and 2019 that a 20% decrease in train transportation costs generate an increase in the volume of modal transportation mode of 15% to 19% and a 40% decrease generate an increase of 33% to 40%. For the period in between 2020 and 2023 the increase in the volume of modal transportation mode of 25% to 39% is sharper than increase in period in between 2019 and 2019 when decreasing the train transportation cost in 20%. In the case of a decrease of 40% in train transportation costs the increase in volume goes from 47% to 63%.



Scenario	Cost 0.038 US$/ton_km [ton/year]	Cost 0.031 Us$/ton_km [ton/year]	Cost 0.023 Us$/ton_km [ton/year]
Base	3,626,533	4,205,220	4,951,924

Table 1.16: Sensitivity analysis of train transportation costs. Period 2016 – 2019.

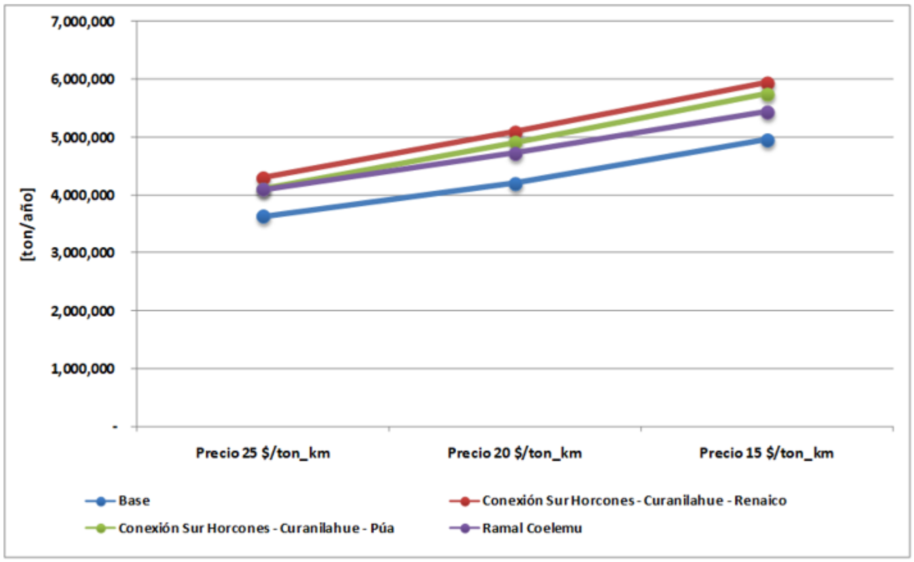


Figure 1.13: Sensitivity analysis of train transportation costs. Period 2016 - 2019.

1.3 Company problem description

The objective of this work is to study the inclusion of rail freight into the transport matrix of a relevant forestry company in southern Chile. To carry out this study, the company provided detailed information over an 8-year period forecasts of the flows between the origins of the wood and the consumption centers (pulp mills, sawmills and board plants) for the area under study.

The truck transport system considers the existence of a road infrastructure not limited by capacity that allows a set of empty trucks to travel to different origins where they are loaded with wood. Each truck then travels to a specific destination where it must wait until it is unloaded. Once serviced, the empty truck is available again to repeat the transport process.

Since the country's existing rail infrastructure consists of a main line that is located in the center of the country plus different branches to the coast and the mountains (see Figure 1.14), the transportation mode from origins to the consumption centers must be bimodal, i.e., a short truck trip from the origin to a transference station o node plus a train trip from the transference node to the final destination.

We intend to compare the modalities of bimodal transport versus direct by truck transportation for all wood flows in the long term.

Figure 1.14: Railroad for Southern Chile.

The comparison is made for each origin and destination pair and considers the alternative costs of each mode of transportation.

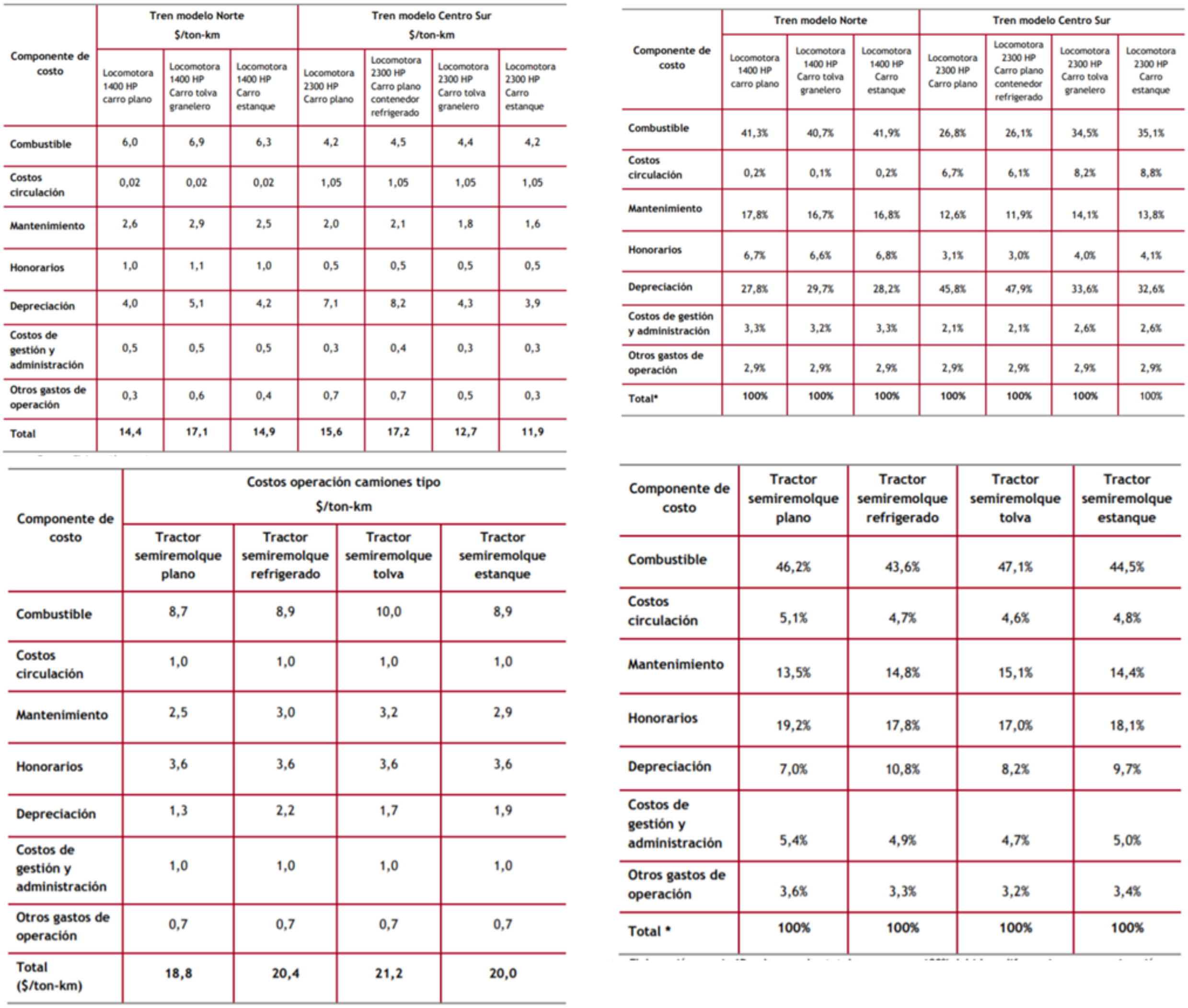
A first approximation to the alternative costs of these transportation options that allow an objective comparison is made according to the structure of operational costs proposed by [17], in which the authors analyze the alternative of comparing transportation rates versus cost structures of transportation modes. According to [17], the latter is the most objective option to make a comparison leaving out market imperfections that could be contained in rates.

Additionally, the authors propose a cost structure based on the operating costs of the transport operators, leaving out the distortions that might exist when considering payments for the use and maintenance of infrastructure.

The cost structure considers the following items:

- fuel.
- circulation costs (vehicle insurance, traffic rights).
- vehicle maintenance (tires, lubricants, maintenance services and other materials).
- personnel (drivers / crew, operation personnel).
- depreciation of the fleet.
- management and administration costs
- other operating expenses (weighing, on route expenses, other operational costs).

Depending on the availability of equipment in the area under study, we define a railway load equipment with a load capacity of 840 tons and a road load equipment of 25 tons [17]. Figure 1.15 details the cost summaries in $ / ton-km of both alternatives. The train transportation cost of $ 15.6 Ton-Km is competitive compared to the cost of $ 18.8 / Ton-Km of truck transport. Additionally, in the case of transport by train, the depreciation of the equipment corresponds to 46% of the total rate, with fuel and personnel being only 29% of the total cost, under circumstances that the transport cost per truck, the personal plus fuel costs represents 65% of its total cost, the fare of the train being more stable compared to external changes.



Componente de costo	Tren modelo Norte $/ton-km			Tren modelo Centro Sur $/ton-km			
	Locomotora 1400 HP carro plano	Locomotora 1400 HP Carro tolva granelero	Locomotora 1400 HP Carro estanque	Locomotora 2300 HP Carro plano	Locomotora 2300 HP Carro plano contenedor refrigerado	Locomotora 2300 HP Carro tolva granelero	Locomotora 2300 HP Carro estanque
Combustible	6,0	6,9	6,3	4,2	4,5	4,4	4,2
Costos circulación	0,02	0,02	0,02	1,05	1,05	1,05	1,05
Mantenimiento	2,6	2,9	2,5	2,0	2,1	1,8	1,6
Honorarios	1,0	1,1	1,0	0,5	0,5	0,5	0,5
Depreciación	4,0	5,1	4,2	7,1	8,2	4,3	3,9
Costos de gestión y administración	0,5	0,5	0,5	0,3	0,4	0,3	0,3
Otros gastos de operación	0,3	0,6	0,4	0,7	0,7	0,5	0,3
Total	**14,4**	**17,1**	**14,9**	**15,6**	**17,2**	**12,7**	**11,9**

Componente de costo	Tren modelo Norte			Tren modelo Centro Sur			
	Locomotora 1400 HP carro plano	Locomotora 1400 HP Carro tolva granelero	Locomotora 1400 HP Carro estanque	Locomotora 2300 HP Carro plano	Locomotora 2300 HP Carro plano contenedor refrigerado	Locomotora 2300 HP Carro tolva granelero	Locomotora 2300 HP Carro estanque
Combustible	41,3%	40,7%	41,9%	26,8%	26,1%	34,5%	35,1%
Costos circulación	0,2%	0,1%	0,2%	6,7%	6,1%	8,2%	8,8%
Mantenimiento	17,8%	16,7%	16,8%	12,6%	11,9%	14,1%	13,8%
Honorarios	6,7%	6,6%	6,8%	3,1%	3,0%	4,0%	4,1%
Depreciación	27,8%	29,7%	28,2%	45,8%	47,9%	33,6%	32,6%
Costos de gestión y administración	3,3%	3,2%	3,3%	2,1%	2,1%	2,6%	2,6%
Otros gastos de operación	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%
Total*	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	100%

Componente de costo	Costos operación camiones tipo $/ton-km			
	Tractor semiremolque plano	Tractor semiremolque refrigerado	Tractor semiremolque tolva	Tractor semiremolque estanque
Combustible	8,7	8,9	10,0	8,9
Costos circulación	1,0	1,0	1,0	1,0
Mantenimiento	2,5	3,0	3,2	2,9
Honorarios	3,6	3,6	3,6	3,6
Depreciación	1,3	2,2	1,7	1,9
Costos de gestión y administración	1,0	1,0	1,0	1,0
Otros gastos de operación	0,7	0,7	0,7	0,7
Total ($/ton-km)	**18,8**	**20,4**	**21,2**	**20,0**

Componente de costo	Tractor semiremolque plano	Tractor semiremolque refrigerado	Tractor semiremolque tolva	Tractor semiremolque estanque
Combustible	46,2%	43,6%	47,1%	44,5%
Costos circulación	5,1%	4,7%	4,6%	4,8%
Mantenimiento	13,5%	14,8%	15,1%	14,4%
Honorarios	19,2%	17,8%	17,0%	18,1%
Depreciación	7,0%	10,8%	8,2%	9,7%
Costos de gestión y administración	5,4%	4,9%	4,7%	5,0%
Otros gastos de operación	3,6%	3,3%	3,2%	3,4%
Total *	**100%**	**100%**	**100%**	**100%**

Figure 1.15: $/Km_Ton cost under national transportation standard (2015).

The results presented are promising for the bimodal transport alternative, however they correspond to transport operations with high degrees of operational efficiency. This aspect is especially relevant given the high % share of fixed costs in the rail service cost structure that could have an important effect on the associated costs in case of not making intensive use of train transport capabilities.

This point is particularly important given the large amount of idle time of the rail infrastructure in southern Chile. This is an important opportunity to take advantage of the economies of scale that the train alternative could offer.

In the case of forest transport by truck, this is an activity that operates with high levels of efficiency in southern Chile, with an intensive use of economies of scale, with a large market with rates that reflect a high level competition and very limited profitability rates which is an important barrier to the entry of substitute means [1].

An adequate railroad evaluation should not avoid any of the infrastructure investments required for a correct operation of railroad services. The Chilean national railroad company requested a strategic study which defined the potential demand for each one of the existing stations, defining the investments required in each one of them. In the study, we estimate the potential railroad freight of forestry products for the next ten to fifteen years, based on the localization of supply of logs and demands points as well as the available railway infrastructure and costs.

1.4 Forestry supply chain hierarchic planning model

The planning of the forestry supply chain that considers all the involved elements is a difficult problem due to the large number of decisions and considerations that must be taken into account. The planning of this supply chain includes both long-term decisions such as investment decisions, as well as decisions that must be made in a period not exceeding one week, by example, the adjustments of the different train itineraries according to the variations of the supplies and demands.

In [9] Cranic argues about the complexity of the different freight transport systems that involve a large amount of human and material resources with a significant amount of relationships and trade-offs between the various administration policies and decision levels. In order to simplify this scenario, he proposes a specific taxonomy to classify these policies into those three levels of planning: strategic, tactical and operational.

This hierarchical classification of the decision levels for the planning of a freight transport system determines the associated information flows in which each level must deliver the necessary information for the decision making of the higher level. These hierarchical relationships allow the formulation of different models associated with specific problems of each of the decision levels.

According to the taxonomy described in [13], it is intended to formulate a strategic planning problem that allows the definition of:

- The investments required to implement a bimodal transport system for trucks and trains in terms of equipment (locomotives and cars).
- The quantity and location of the optimal transfer stations and the facilities required at the destinations.
- The optimal truck fleet required to supply the trip from the origins of the forest products to the transfer stations.
- The optimal truck fleet required to perform the transport fraction only by truck.
- The definition of flows between origins and transfer stations and between origins and

destinations of minimum cost.
- The services to be implemented in rail freight planning and the optimal equipment configuration to fulfill those services.

In the case of rail investments, the cost of transportation is largely affected by scale economics, since in order to be an efficient and competitive alternative, it must be able to distribute large investments in a very large amount of freight. Then, the representation of transport costs by train will be non-linear and decreasing functions by sections. This function structure is explained mainly by the high levels of fixed costs that will be distributed decreasingly as the load transported increases until the equipment is occupied completely. In order to increase the transported volume, additional equipment must be incorporated with very high marginal costs which will decrease again as the transported load increases.

Given the low level of utilization of the railway infrastructure in the area, the possibilities of congestion of rail traffic will be minimal, being modeled only as a standard waiting time when operating on a minimum number of daily trips.

A good strategic planning of this supply chain is of great value because it ensures a balanced supply of raw materials to the different industrial consumption centers and minimizes the costs of transferring raw materials from the origins to the destinations across the chain.

Clearly, given the size and complexity of the problem, it is expected that this set of decisions can be supported by some computational tool based on optimization algorithms that allow this activity to be performed systemically and repetitively.

1.5 Cost parameters for the model

We present the costs of the different activities involved in the supply chain under study. First of all, we introduce the costs associated with Truck trips. This study is carried out according to the definition of [17] with the exception of circulation costs, which are calculated independently of the standard travel cost in $ / km-ton, that is, we calculate the circulation costs of each trip. The foregoing is justified given the great variability in circulation costs in the study area, therefore having an important impact on the choice of transportation alternatives for each origin. To achieve this, and according to tables in Figure 1.15, 1 ($ / ton-km) is discounted from the cost of the trip and then the circulation cost calculation ($ / ton-km) is incorporated for each origin and destination pair.

To value the entire trip by truck between a tuple origin and destination, we must consider the following aspects:

- the cost of the empty truck trip to the origin.
- The cost of empty truck travel on the way to the origin.
- the cost of waiting for the truck at the origin.
- the cost of loading timber at the origin.
- the cost of transporting the truck loaded with wood from the origin to the destination.

- the cost of circulation of the truck loaded with wood from the origin to the destination.
- the cost of the waiting time of the truck at the destination door.
- and the cost of downloading at destination.

The cost of the loaded trip is calculated based on the cost structure proposed in [17]. This factor corresponds to the paved transport standard at standard circulation speed. In the case of forest transport in southern Chile, approximately 30-40% of the trips are made on roads with gravel or dirt folders and high slopes, which mainly affects fuel consumption and vehicle maintenance. As a way to represent this situation is that there we apply a transformation of the distances of "trips in non-standard conditions" in equivalent distances in standard conditions by a "Standard Correction" factor that according to historical background of the forestry sector in southern Chile approximates the value 2.31 ([Reference to gravel / paved correction factor]).

Additionally, the loaded truck rate considers a "productivity factor" that is a non-linear function of the total hours used by each truck of a contract in a month , which allows to reflect a common benefit policy between the transport operator and the company requesting the service. The company delivers more products to the operator to the extent that it is more productive and in return, applies a lower rate.

In order to calculate the hours of work assigned to each truck, a standard is used that considers the use of an circulation average speed of 60 (km / hour),for both the hours of loaded and unloaded truck travels plus a standard for load and unload waiting times of 40 (minutes / trip) each. The final formula for travel times used by truck is:

Travel_Time (Hours/travel)= (Kilometers_standard_trip_origin_destination + kilometers_not_standard_trip_origin_destination * 2 .31) * 2 / 60 + (40 * 2) / 60

Circulation costs are represented by the payment of both private and public tolls associated with each of the routes used in the truck transport operation. In order to bring the cost of tolls to units ($ / ton) it is necessary to consider a standard of load per trip per truck (ton / trip). According to the law of transport of cargo in force in Chile, the maximum weight to be transported is 45 tons / trip and given the truck fares in use between 17 to 19 tons / truck, the maximum net weights to be transported would be 28 tons / trip, standard that are used in this study (assuming a very efficient truck transport system).

For the purposes of this study, the cost of the empty trip is simplified assuming that it has the same cost as the trip charged. Although this is a quite strong assumption in theory, Chilean forestry statistics show that the actual costs of empty trips are quite stable and are fairly well represented with the corresponding loaded trip.

Load/unload costs are associated with a flat rate per ton.

In the case of waiting time cost at origin, a fixed waiting time is assumed which is represented by a fixed cost per ton. This definition is based on the intensive use of the ASICAM optimization system in the Chilean forest industry, which allows trucks to be routed in such a way that synchronization of the arrival to the origins is achieved avoiding congestion and controlling the waiting times and associated costs.

In the case of destinations costs, these are mainly associated with waiting times at the doors of the wood processing plants. Unfortunately, there has not been achieved the same level of efficiency in the destinations than of origins in the control of waiting times, allowing the existence of waiting lines even in the design of the transport solution. Consequently, the waiting costs at destination are highly dependent on congestion times and represented as a function of a non-linear nature of the size of the waiting queue of the trucks at the door of the plant.

For the purposes of this study, the problem of congestion times in destinations is not considered, assuming a fixed cost per ton.

The formulas for the calculation of transport costs per truck, according to the structure of operating costs proposed by [17], would be the following:

Transportation by truck Cost ($/ton) = [Loaded_Trip_Cost ($/ton) + Unloaded_Trip_Cost ($/ton) + Loaded_Circulation_Cost ($/ton) + Unloaded_Circulation_cost ($/ton) + Origin_Load_cost ($/ton) + Destination_Unload_Cost ($/ton) + Origin_Waiting_cost ($/ton) + Destination_waiting_cost ($/ton)] * Productivity_Factor (Efective_Hours_fleet_month)

Loaded_Trip_Cost ($/ton) = (Kilometers_Standard_trip_origin_destination + Kilometers_Not_Standard_trip_origin_destination * 2.31) * (18.8 − 1) ($/ton-km)

Unloaded_Trip_Cost ($/ton) = Unloaded_Trip_Cost ($/ton) = Loaded_Trip_Cost ($/ton)

Loaded_Circulacion_Cost ($/ton) = Loaded_Circulacion_Cost ($/ton) = Total_Toll_Origin_Destination ($/trip) / 28

Unloaded_Circulation_Cost ($/ton) = Unloaded_Circulation_Cost ($/ton) = Loaded_Circulation_Cost ($/ton)

Below are the calculations for the travel cost in bimodal mode. We must consider the following elements:

- the cost of the trip by truck between the origin and a transfer station
- and the cost per train from the transfer station to the destination.

The cost calculation of the truck section of the trip is identical to that used for the trip from an origin to a destination.

In the case of the rail travel costs, the cost structure proposed in [17] could be considered. However, the latter proposition assumes high levels of utilization of the railway infrastructure and equipment in freight transport, which defines a scenario of very efficient and competitive costs. This will not necessarily be the condition that is present when evaluating the incorporation of bimodal transport to the transport matrix of forest products, even more when the competitor is highly efficient and with a large-scale and consolidated operation in the area. This is why we build a "typical train operations cost structure" from scratch for the southern zone of Chile to transport forest products. The parameters for the calculation of travel times and associated costs are the following:

Available working time = 5720 (Hours/locomotive-year)
Load/unload time = 7 (minutes/car)
Train stay time at transference station = 30 to 45 minutes
Train Average Speed = 30 (kilometers/Hour) with interference
40 (kilometers/Hour) without interference
Maximum Train Length = 800 (meters /train)
Locomotive Type = 3.300 HP refurbished 19.5 meters long & 115.8 (Ton). This locomotive is able to travel all over the railroad without weight restrictions
Car Type = Flat 4 axes car and 15.5 meters long, can transport different log dimensions. Given the 19 (ton/axes) law limitations, the gross weight of the car will be 76 (ton/car) and the net weight will be 60 (ton/car)
Maximum number of cars by train (length restriction) = 47 (cars/train)
Maximum number of cars per train (law restriction) = 28 (cars/train)

Operational assumptions:

- All trains are considered to use a route from origin to destination with the same locomotive.
- Only two loading conditions are considered: loaded train and empty train, that is, the trains will be fully loaded from the origin to the destination and completely empty for the return journey.
- Empty travel times and charged travel time are considered equivalent.
- A maximum weight in each car of 19 (ton / axe) is considered. Cars of greater capacity are not analyzed given the current restriction of bridges on the rail route, infrastructure that will not be improved in the medium term.
- Operational availability of locomotive equipment = 85%
- Operational availability of cars = 95%
- Road availability = 83%

The network structure for train transport considers the origin or transfer stations, passing stations, destination stations and railway line. Figure 1.16 identifies all the elements of the proposed network.

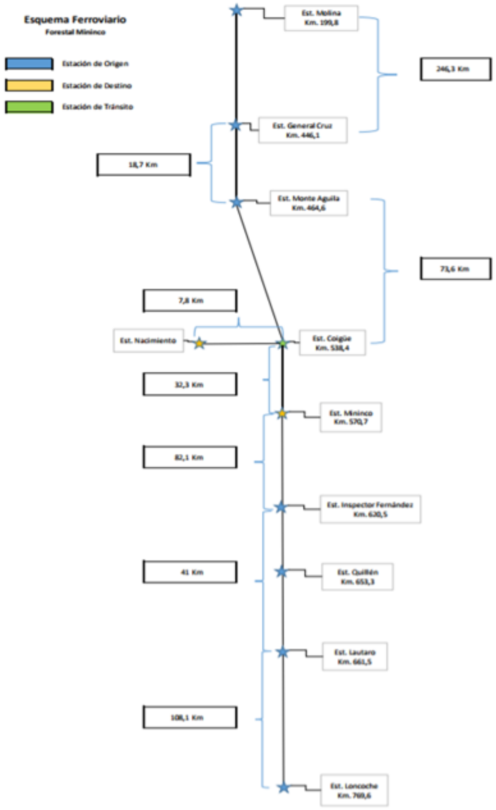


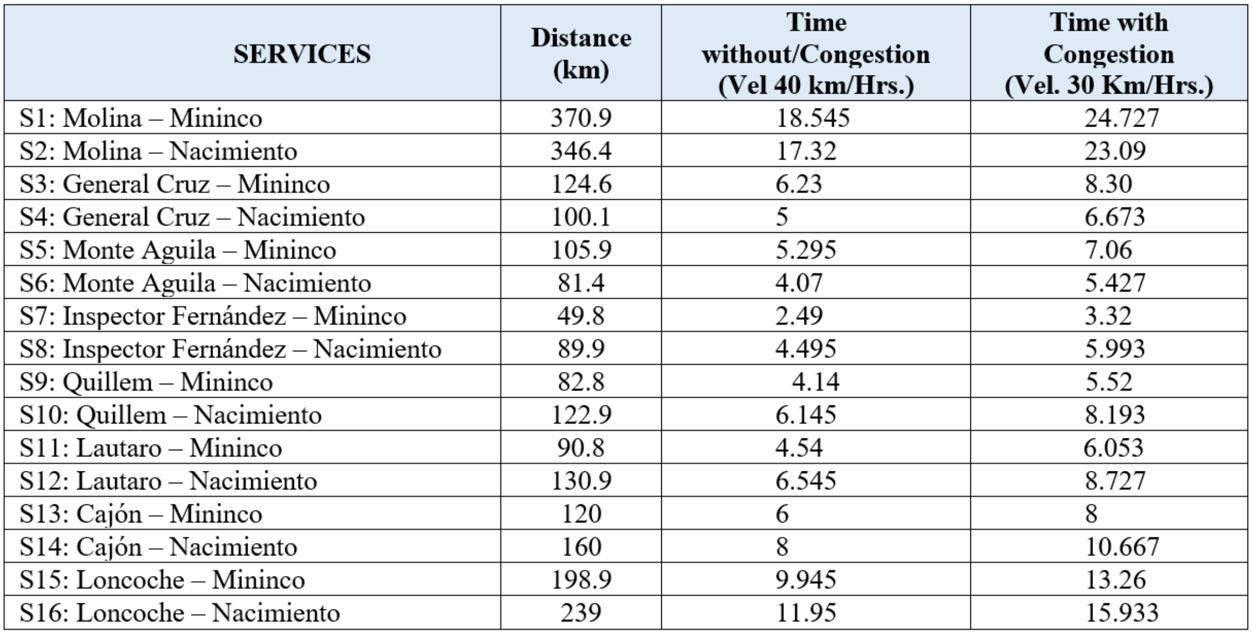
Figure 1.16: Railroad Structure.

The current network structure considers the stations of origin: Molina, General Cruz, Monte Aguila, Inspector Fernández, Quillem, Lautaro, Cajón and Loncoche. The destination stations are Mininco and Nacimiento, with the Coigue pass station existing.

Given this configuration of stations, Table 1.17 shows the list of 16 possible services.

Each of these services can be implemented through various rail operation models. Each operation model has a particular focus on optimizing the railway operation, for example, minimizing total operating costs, minimizing total operating times, minimizing investments. The implementation of one or another model of operations will require a different combination of equipment and will require a specific amount of work hours to execute each of the services.

Depending on the selected operation model and the selected service, it is possible to calculate the total hours of operation required and the necessary equipment configuration. With this information we proceed to calculate the costs associated with the investment required and the operation.



SERVICES	Distance (km)	Time without/Congestion (Vel 40 km/Hrs.)	Time with Congestion (Vel. 30 Km/Hrs.)
S1: Molina – Mininco	370.9	18.545	24.727
S2: Molina – Nacimiento	346.4	17.32	23.09
S3: General Cruz – Mininco	124.6	6.23	8.30
S4: General Cruz – Nacimiento	100.1	5	6.673
S5: Monte Aguila – Mininco	105.9	5.295	7.06
S6: Monte Aguila – Nacimiento	81.4	4.07	5.427
S7: Inspector Fernández – Mininco	49.8	2.49	3.32
S8: Inspector Fernández – Nacimiento	89.9	4.495	5.993
S9: Quillem – Mininco	82.8	4.14	5.52
S10: Quillem – Nacimiento	122.9	6.145	8.193
S11: Lautaro – Mininco	90.8	4.54	6.053
S12: Lautaro – Nacimiento	130.9	6.545	8.727
S13: Cajón – Mininco	120	6	8
S14: Cajón – Nacimiento	160	8	10.667
S15: Loncoche – Mininco	198.9	9.945	13.26
S16: Loncoche – Nacimiento	239	11.95	15.933

Table 1.17: Services between two stations.

The alternative operation models to be evaluated in this study have been developed and prepared by CHENA railway logistics advisory company. The proposed operational models consider the following assumptions:

- If necessary, each destination provides an unload equipment available for the complete operation.
- If necessary, each transference node provides a loading equipment available for the complete operation.
- The cars are grouped into sets of 14 cars. Each “Group of cars” serves a single origin and a single destination on each trip. A locomotive can drag 0, 1 or 2 “car groups”, according to the maximum load allowed.

Three models will be evaluated: model 1A, which optimizes time, model 1B, which optimizes the car at the origin, and model 1C, which optimizes the yard operations. The details for each model are described next.

Model 1A: "Time Optimization Model"

- Operational unit initially constituted by a locomotive and 6 "Car groups".
- Before starting the operations of the period, the locomotive is located next to 4 empty "car groups" in an open destination. There are 2 empty "car groups" located in the farthest transference node.
- The locomotive works always transporting 2 empty "car groups" to origin and 2 loaded "car groups" to destination without waiting times.
- The locomotive only stops to change empty cars for cars loaded at origin and loaded cars by empty cars at destination.
- When the locomotive leaves the empty cars at origin, the loading equipment proceeds to load them immediately and when the locomotive leaves loaded equipment at destination, the unloading equipment proceeds to unload them immediately. In this way, every time the locomotive arrives at its origin or destination, it always has cars ready to transport without requiring waiting times.
- In case of having more tonnage to transport and, therefore, more hours of locomotive for transport, the model allows to increase its transport capacity by adding a new locomotive and 2 "additional car groups".
- If a transference node requires more than one service, the farthest service is operated first and then the closest service.
- In the same way, when there is more than one open transference node, the farthest origin is operated first.
- In both cases, on the last trip of the service, the locomotive transports the empty cars to the new origin and / or destination as appropriate.

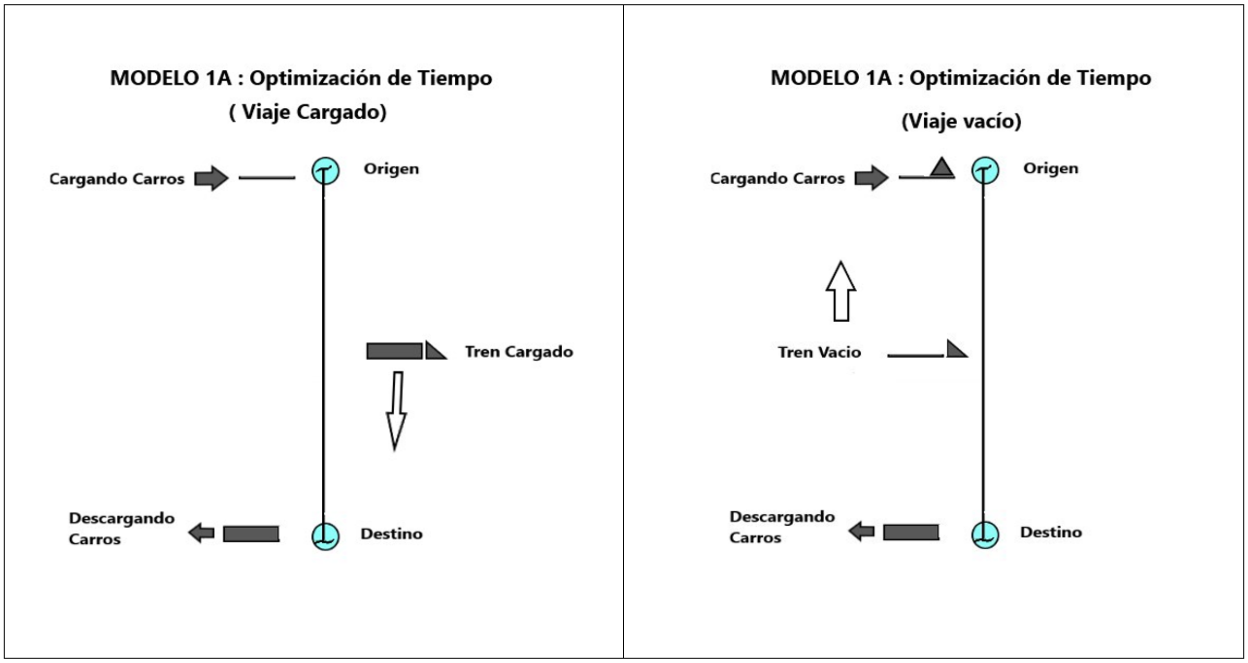


Figure 1.17: Model 1A.

Model 2A: “Car Optimization Model at Origin”

- Operational unit initially constituted by a locomotive and 4 “Car groups”.
- Before starting the operations of the period, the locomotive is located next to 2 empty “car groups” in an open destination. There are 2 empty “car groups” located in the farthest transference nodes.
- The locomotive works always transporting 2 empty “car groups” to origin and 2 “car groups” loaded to destination.
- The locomotive only stops to change empty cars for cars loaded at origin. When the locomotive leaves the empty cars at origin, the loading equipment proceeds to load them immediately.
- When the locomotive arrives at the center of consumption with loaded cars, it proceeds to unload them immediately.
- In this way, every time the locomotive arrives to an open transference node it always has the cars ready to transport without requiring waiting times, instead, when the locomotive arrives at its destination, it must wait for the download process before returning the origin.
- In case of having more tonnage to transport and, therefore, more hours of locomotive for transport, the model allows to increase its transport capacity by adding a new locomotive and 2 “additional car groups”.
- If an open transference node requires more than one service, the farthest service is operated first and then the closest service.
- In the same way, when there is more than one open transference node, the farthest one is operated first.
- In both cases, on the last trip of the service, the locomotive transports the empty cars to the new origin and / or destination as appropriate.

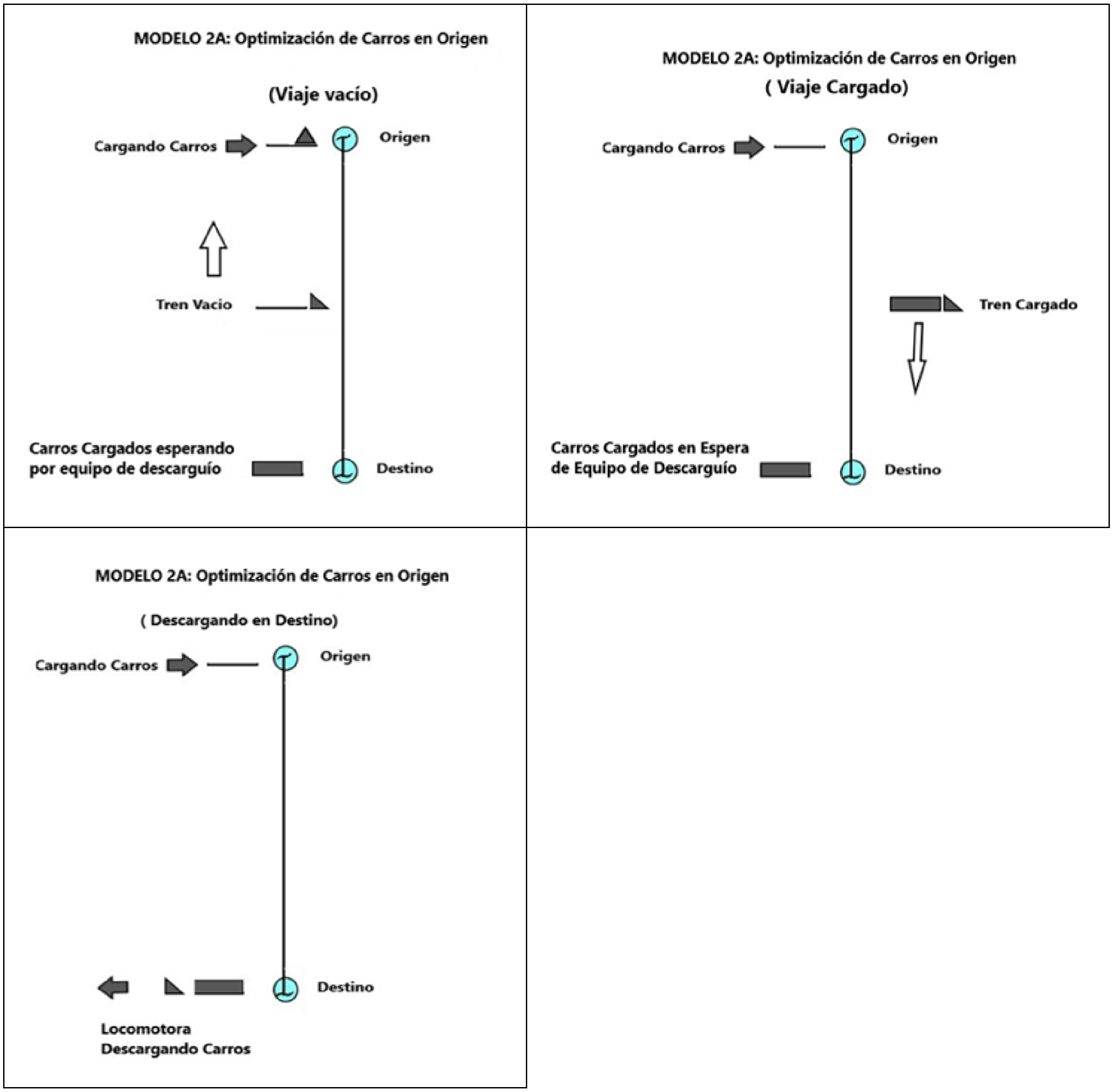


Figure 1.18: Model 2A.

Model 3A: “Yard Optimization Model”

- Operational unit constituted by a locomotive and 2 “Car groups”.
- Before starting the operations of the period, the locomotive is located next to 2 empty “car groups” in a destination.
- The locomotive works always transporting 2 empty “car groups” to origin and 2 “car groups” loaded to destinations.
- When the locomotive arrives with unloaded cars, it proceeds to load them immediately.
- When the locomotive arrives at its destination with loaded cars, it immediately unloads them.
- In case of having more tonnage to transport and, therefore, more hours of locomotive for transport, the model allows to increase its transport capacity by adding a new locomotive and 2 “additional car groups”.
- If a transference node requires more than one service, the farthest service is operated first.
- In the same way, when there is more than one open origin, the furthest origin is operated first.
- In both cases, on the last trip of the service, the locomotive transports the empty cars to the new origin and / or destination as appropriate.

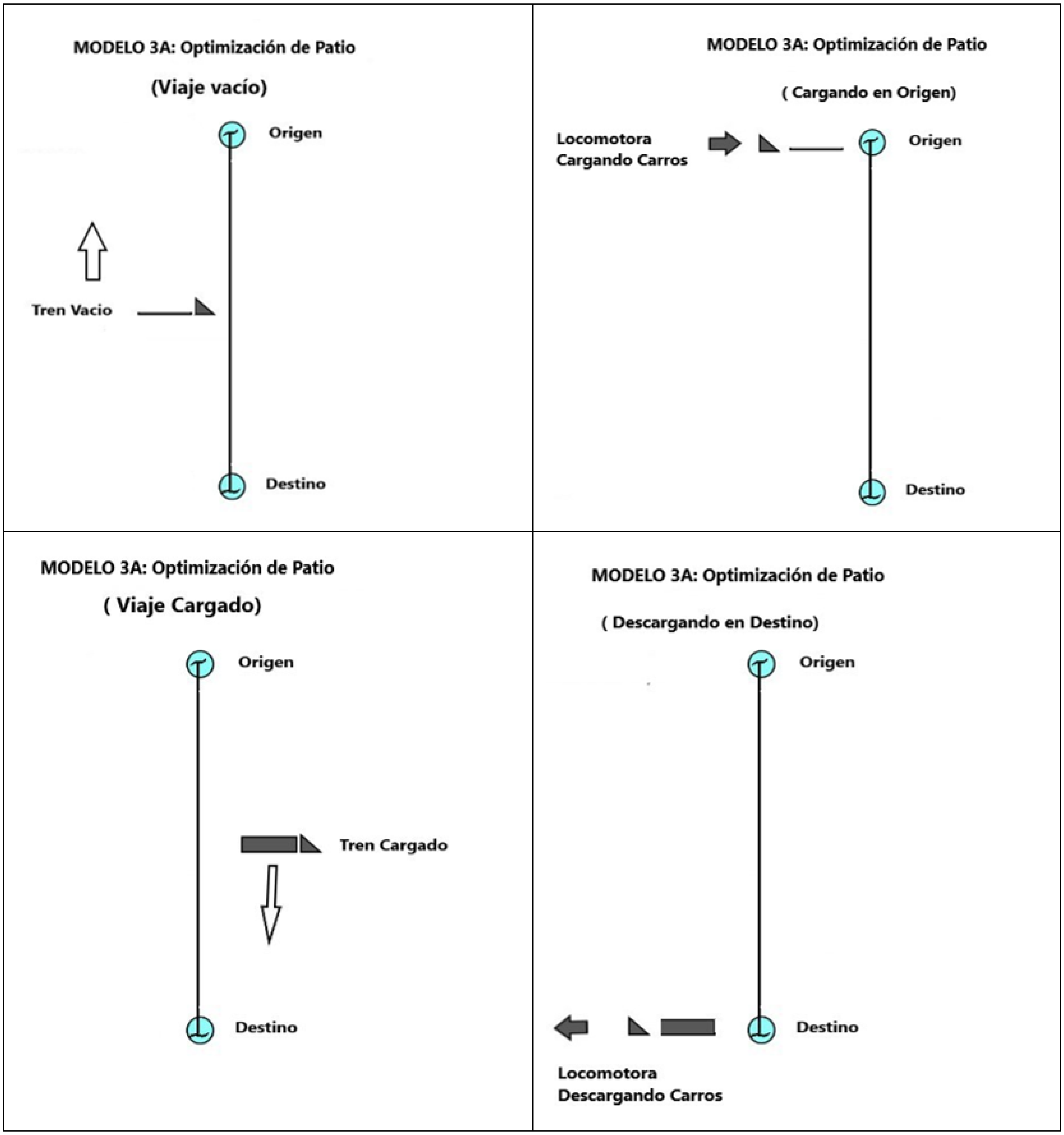


Figure 1.19: Model 3A.

Based on the standard costs indicated in Table 1.18, the cost curves of each of the 3 models to be evaluated are constructed based on the amount of work required. These functions will be modeled in terms of fixed costs and variable operating costs required by the equipment.

Investment Cost (locomotive & cars)	locomotive: 2.870.000 USD Car unit cost: 86.000 USD
Workforce	Driver: 1.427.019 CLP/month Driver Assistant: 941.892 CLP/month Yard Supervisor 1.427.019 CLP/month
Fuel (Diesel)	Correction factor 25%. Long Term fuel cost 230 CLP / liter Station Consumption, 20% notch 1, 80% idle Interference Consumption, 100% idle
Locomotive & Cars maintenance	Locomotive maintenance: 720 CLP/km. Maintenance workforce: 2.736.856 CLP/month/80 car Monthly maintenance: 22.381 CLP/month/car Maintenance by traveled kilometer: 18178 CLP/-car/1000 km
Tolls	Variable: 0,071 UF / 1000 TKBC Fixed: 17,74% of 2.050 million CLP Canon: 17,74% of 40.000 UF 17,74% correspondent to the fraction of forestry transportation using EFE infrastructure ($406,54/ton)
External Services	Equivalent to 30% of workforce
Insurance	3.53% over total costs
General Expenses	10% over total costs
Unforeseen	8% over total costs
Load/Unload equipment	1.980.000 CLP/unit x month, includes investment depreciation, operational costs and workforce

Table 1.18: Standard cost table.

Figure 1.20 shows by-train transportation unitary cost for the proposed models based on the total number of tons transported by train in the evaluation period.

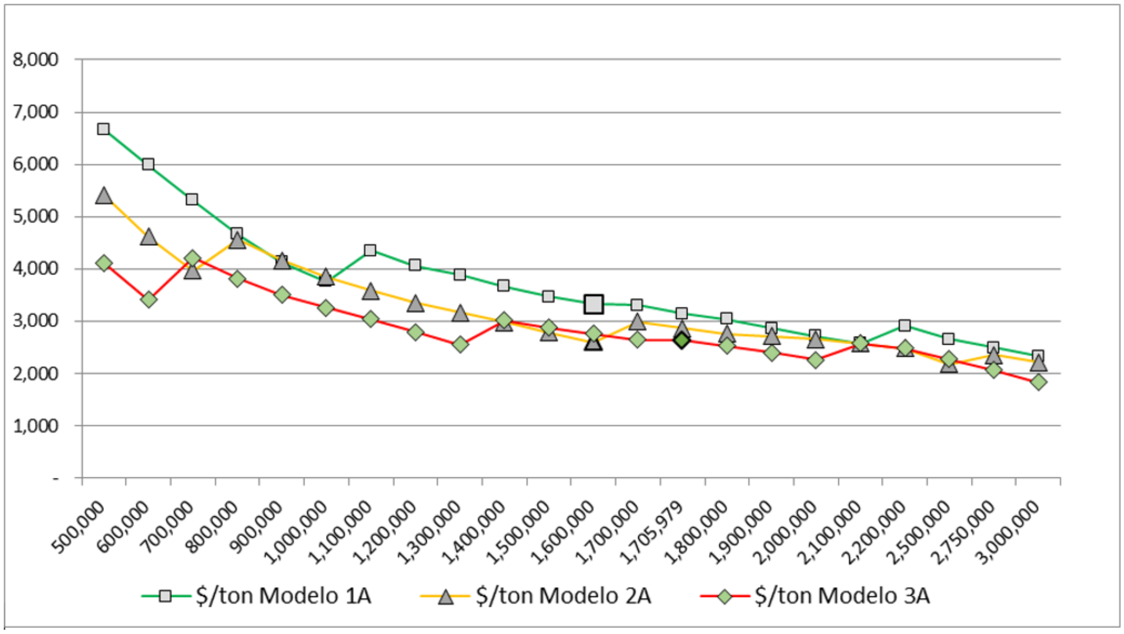


Figure 1.20: Unit Costs ($/Ton) by train transportation mode for each operational model.

Figure 1.20 shows that the unit cost curves ($ / Ton) based on the total tons transported (Ton / year) are non-linear in nature and decreasing by sections, which is explained by the limited availability of operational hours for the railroad transport equipment and its high investment value. This characteristic allows us to approximate this cost structure through a linearization by sections, which allows modeling the problem through first-order equations.

1.6 Bimodal supply chain strategic planning

The problem of strategic planning of the bimodal supply chain of forest products will determine the wood flows that will go directly from the origins to the destinations by truck and the flows that will go through transference stations. To achieve this, the optimal fleets of trucks and trains required will be determined, in the latter case including the necessary long-term investments in locomotives, cars and equipment in transfer stations. Finally, the optimal services to be implemented in rail freight planning will be evaluated.

Next is the mixed integer linear programming model developed to solve this problem. The temporal variable is modeled through discrete intervals of duration equal to 1 year. It is assumed that at the beginning of the planning horizon all equipment is available according to the requirement of each of the operation models evaluated.

Parameters

I	Set of origins of forestry products
J	Set of bimodal transference nodes
K	Set of destinations for forestry products
T	Set of planning periods
C	Set of truck fleets. Each fleet is defined by a set of trucks and has its own transportation cost parameters
B	Set of railroad transportation models. Each model uses a different configuration of equipment and is associated with a specific goal, by example, minimize operational times or minimize total investment. Each model allows to implement one or more freight services
M	Set of forestry products
$\mathrm{i}toj$	Origins i that are associated to a specific transference node j
$\mathrm{i}tok$	Origins i that are associated to a specific destination k
$jtok$	Transference nodes j that are associated to a specific destination k
$\mathrm{i}mt$	Product m is available in origin i in period t
kmt	Product m is demanded in destination k in period t
r	Set of "operation ranges" r. It allows us to discriminate minimum and maximum operating hours for a specific equipment. Beginning with a cheap equipment (minimum investment) in the lowest range, it is possible to raise the investment and operational hours as the range grows
r_{ant}	Set of previous ranges of range r
A	Set of planning periods
$atot$	Periods associated to a specific planning year
$oferta_{\mathrm{i}mt}$	Tons of product m available in origin i in period t
$\mathrm{de}manda_{kmt}$	Tons of product m demanded in destination k in period t
Mr_{ar}	Maximum and minimum quantity of available hours associated to a specific range r
Cj_j	Installation cost of transference j
$Cjmf_{jb}$	Implementation cost of service model b starting in transference node j
Ck_k	Installation cost in destination k
$CFjr$	Total investment plus fixed cost required to implement model b in operation range r
$CX\mathrm{i}j$	Truck transportation Unit Cost in between origin i and transference node j
$CF\mathrm{i}k$	Truck transportation Unit Cost in between origin i and destination k
$CP\mathrm{i}j$	Truck circulation Unit Cost in between origin i and transference node j
$CP\mathrm{i}k$	Truck circulation Unit Cost in between origin i and destination k
$CE\mathrm{i}j$	Truck waiting time Unit Cost in between origin i and transference j
$CE\mathrm{i}k$	Truck waiting time Unit Cost in between origin i and destination k
$HF\mathrm{i}k_{\mathrm{i}k}$	Truck transportation time (hours/trip) in between origin i and destination k
$HF\mathrm{i}j_{\mathrm{i}j}$	Truck transportation time (hour/trip) in between origin i and transference j
$HFjk_{bjk}$	Train model b transportation time (hour/trip) in between transference j and destination k. Includes load/unload times when the activity is performed by the transportation locomotive

$KMjk_{jk}$	Kilometers in between transference j and destination k
$LTjk_{jk}$	Fuel liters used by a locomotive to perform a trip in between transference j and destination k
$FProd_c$	Productivity factor associated to truck fleet c
$Flicit_c$	Bidding factor associated to truck fleet c
$HrFl_c$	Standard yearly working hours for truck in fleet c
$Flota_{ac}$	Total amount of trucks in fleet c
$TonCamion$	Total net ton transported by truck
$TonFfcc$	Total net ton transported by train
$CombFfcc$	Locomotive fuel value (\$/liter)
$MantLocomotora$	Locomotive Maintenance Cost (\$/kilometer)
$MantCarroKm$	Car Maintenance Cost (\$/kilometer)
$PeajeVarFfcc$	Train Toll Unit Cost (\$/ton_km)
$PeajeFijoFfcc$	Train annual Cost (\$/year)
$PesoTaraFfcc$	Train tare weight (Ton)

Variables

$x_{imtjc} \in \mathbb{R}^+$	Flow of product m in between origin i and transference j in period t with truck fleet c
$f_{imtkc} \in \mathbb{R}^+$	Flow of product m in between origin i and destination k in period t with truck fleet c
$z_{jmtkb} \in \mathbb{R}^+$	Flow of product m in between transference j and destination k in period t with train model b
$WJ_j \in \{0,1\}$	1 if transference j active, 0 otherwise
$WJMF_{ajb} \in \{0,1\}$	1 if transference j active with train model b in year a, 0 otherwise
$WK_k \in \{0,1\}$	1 if destination k is active to train receptions, 0 otherwise
$V_{rb} \in \{0,1\}$	1 if range r active with model b, 0 otherwise
$Hik_{ac} \in \mathbb{R}^+$	Truck effective Hours of transportation from origins to destinations in year a with fleet c
$Hij_{ac} \in \mathbb{R}^+$	Truck effective Hours of transportation from origins to transferences in year a with fleet c
$Hjk_{ab} \in \mathbb{R}^+$	Train effective Hours of transportation from transference nodes to destinations in year a with model b
$Hjkr_{abr} \in \mathbb{R}^+$	Train effective Hours of transportation from transference nodes to destinations in year a with model b in range r
$Kjk_{ab} \in \mathbb{R}^+$	Total distance transported by train in between transference nodes and destinations in year a with model b
$Tjk_{ab} \in \mathbb{R}^+$	TKBC (Ton kilometers Gross Loaded) by train in between transference nodes and destinations in year a with model b
$Ljk_{ab} \in \mathbb{R}^+$	Total Fuel (Liters) consumption by train transportation in between transference nodes and destinations in year a with model b
$CREQ_{ac} \in \mathbb{R}^+$	Total amount of trucks required in year a by fleet c
$TFC_a \in \mathbb{R}^+$	Total amount of money (\$/year) spent in truck transportation in year a
$TFT_a \in \mathbb{R}^+$	Total amount of money (\$/year) spent in train transportation in year a

Objective function

$$Min \sum_a (TFC_a + TFC_a) + \sum_j WJ_j * CJ_j + \sum_k WK_k * CK_k + \sum_{ajb} WJMF_{ajb} * Cjmf_{jb} \tag{1.1}$$

Restrictions

$$\sum_{c,itoj} x_{imtjc} + \sum_{c,kmt} f_{imtkc} = oferta_{imt} \qquad \forall imt \tag{1.2}$$

$$\sum_{c,imt} f_{imtkc} + \sum_{b,jtok} z_{jmtkb} = \mathrm{demanda}_{kmt} \qquad \forall kmt \tag{1.3}$$

$$\sum_{c,imt} x_{imtjc} + \sum_{b} z_{jmtkb} = 0 \qquad \forall kmt, jtok \tag{1.4}$$

$$WJ_j * BIGM - \sum_{c,imt} x_{imtjc} = 0 \qquad \forall j \tag{1.5}$$

$$WK_k * BIGM - \sum_{kmt,jtok,b} z_{jmtkb} = 0 \qquad \forall k \tag{1.6}$$

$$WJMF_{ajb} * BIGM - \sum_{kmt,jtok,atot} z_{jmtkb} = 0 \qquad \forall a, j, b \tag{1.7}$$

$$\frac{\sum_{kmt,imt,atot} f_{imtkc}}{Toncamion} * HFik_{ik} - Hik_{ac} = 0 \qquad \forall a, c \tag{1.8}$$

$$\frac{\sum_{imt,itoj,atot} x_{imtjc}}{TonCamion} * HFij_{ij} - Hij_{ac} = 0 \qquad \forall a, c \tag{1.9}$$

$$\frac{(Hik_{ac} + Hij_{ac})}{HrFl_c} - CReq_{ac} = 0 \qquad \forall a, c \tag{1.10}$$

$$Flota_{ac} - CReq_{ac} <= 0 \qquad \forall a, c \tag{1.11}$$

$$\frac{\sum_{kmt,jtok,atot} z_{jmtkb}}{TonFfcc} * HFjk_{bjk} - Hjk_{ab} = 0 \qquad \forall a, b \tag{1.12}$$

$$\frac{\sum_{kmt,jtok,atot} z_{jmtkb}}{TonFfcc} * KMjk_{jk} - Kjk_{ab} = 0 \qquad \forall a, b \tag{1.13}$$

$$\frac{\sum_{kmt,jtok,atot} z_{jmtkb}}{TonFfcc} * LTjk_{jk} - Ljk_{ab} = 0 \qquad \forall a, b \tag{1.14}$$

$$Kjk_{ab} * (PesoTaraFfcc * 2 + PesoNetoFfcc) - Tjk_{ab} = 0 \qquad \forall a, b \tag{1.15}$$

$$Hjk_{ab} - \sum_{r} Hjkr_{abr} = 0 \qquad \forall a, b \tag{1.16}$$

$$V_{rb} * Mr_{ar_{ant}} - Hjkr_{abr} = 0 \qquad \forall a, b, r, r_{ant} \tag{1.17}$$

$$Hjkr_{abr} - V_{rb} * Mr_{ar} = 0 \qquad \forall a, b, r \tag{1.18}$$

$$\sum_{r} V_{rb} <= 1 \qquad \forall b \tag{1.19}$$

$$\begin{aligned}&\left(\sum_{\mathrm{i}mt,\mathrm{i}to j,atot,c} (CX\mathrm{i}j_{\mathrm{i}j} + CE\mathrm{i}j_{\mathrm{i}j} + CP\mathrm{i}j_{\mathrm{i}j}) * x_{\mathrm{i}mtjc}\right.\\ &\quad \left. + \sum_{kmt,\mathrm{i}mt,atot,c} (CF\mathrm{i}k_{\mathrm{i}k} + CE\mathrm{i}k_{\mathrm{i}k} + CP\mathrm{i}k_{\mathrm{i}k}) * f_{\mathrm{i}mtkc}\right)\\ &\qquad *(Flicit_c + FProd_c) - TFC_a = 0 \qquad \forall a\end{aligned} \tag{1.20}$$

$$\begin{aligned}&\left[\sum_{b,r} CFjr_{br} * V_{rb} + \sum_{b} Kjk_{ab} * (ManTCarrKm + MantLocomotora * 2)\right.\\ &\quad \left. + \sum_{b} (Ljk_{ab} * CombFfcc + Tjk_{ab} * PeajeVarFfcc)\right]\\ &\qquad *(1 + \%Seguro + \%Imprevistos) - TFT_a = 0 \qquad \forall a\end{aligned} \tag{1.21}$$

The objective function (1.1) minimizes the sum of truck and train costs plus investment required on both transfer nodes and destinations. Restrictions (1.2), (1.3) and (1.4) ensure the balance of the flow of forest products from the origin to destinations or to transference nodes and from transference nodes to destinations by train. Restriction (1.5) activates the installation of each transference node and the investments in equipment necessary to operate them. Restriction (1.6) activates the reception of forest products via train and the investments in equipment required to operate them. Restriction (1.7) activates the fixed cost of cargo equipment required to operate a train service in the transference node. Restrictions (1.8) and (1.9) calculate the total transportation hours required for each fleet to transport forest products from the origins to the final destinations and to the transference nodes.

Restrictions (1.10) and (1.11) allow to calculate the number of trucks required of each fleet, determining the optimal fleet size for the problem. Restrictions (1.12), (1.13) and (1.14) allow us to calculate the total transportation hours required for each train transport model, the kilometers traveled, and the liters of fuel required to do it. This additional background is necessary to proceed to calculate the variable operating costs of the train. The restriction (1.15) allows to calculate the TKBC (Tons full gross kilometers) KPI obtained from calculating the gross tons transported by the kilometers traveled. Restriction (1.16) activates a specific range of train transport hours: each range is associated with an investment level. As the range active increases, it also happens with the investment levels and consequently the availability of train transportation hours.

Restrictions (1.17), (1.18) and (1.19) allow to control the correct activation of time ranges, that is, from the first ranges with less available hours and higher costs to the ranges with greater number of hours available and lower transportation costs. Working bounded to a specific range ensures the linearity of the costs in that range. Restrictions (1.20) and (1.21) determine the total annual transportation costs by truck and by train.

The proposed model[1] was applied for a 8-year strategic planning of transportation resources of a Chilean forestry company, including 80 MM tons from 2,000 different forest

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[1] The model was developed in GAMS/Cplex 24.1.3.

origins to 24 destinations, using 5 transfer fields and two final destinations for train/truck combination, which concentrate approximately 60% of the total volume transported in the planning period.

Given the need to make investment decisions for a long planning period, the evaluation considered a set of scenarios with the purpose of analyzing the robustness of decisions against changes in operating conditions.

We analyzed scenarios for the 3 proposed operation models with upper limits in the total ton by train from 10% to 50% for the 2 destinations with train option. In each case, the resulting truck transport model and its operational feasibility were analyzed.

1.7 Results

According to the results obtained, model 3A has the lowest cost for most of the scenarios analyzed. Model 3A is only overperformed in scenarios of highest train volume and low use of train-scale economics due to the increase of services at stations closest to the consumption centers, making the time used for loading and transportation more relevant (see Figure 1.21).

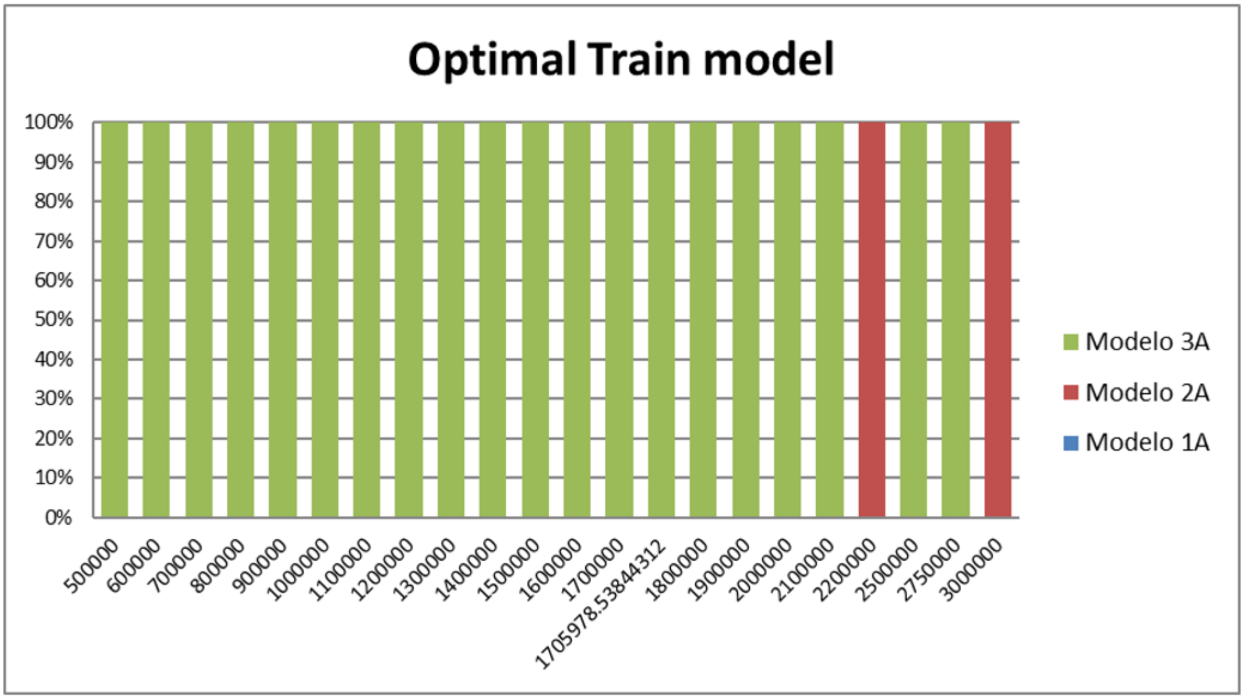


Figure 1.21: Optimal train transportation models.

The optimal scenario (minimum total transport cost) is obtained for an average transport of 1,706MM (Ton / year), being 9% cheaper than truck-only transport (see Figure 1.22). The scenarios between 1.5 MM Ton / year and 2 MM Ton / year have a cost differential of less than 1% with respect to the optimal scenario.

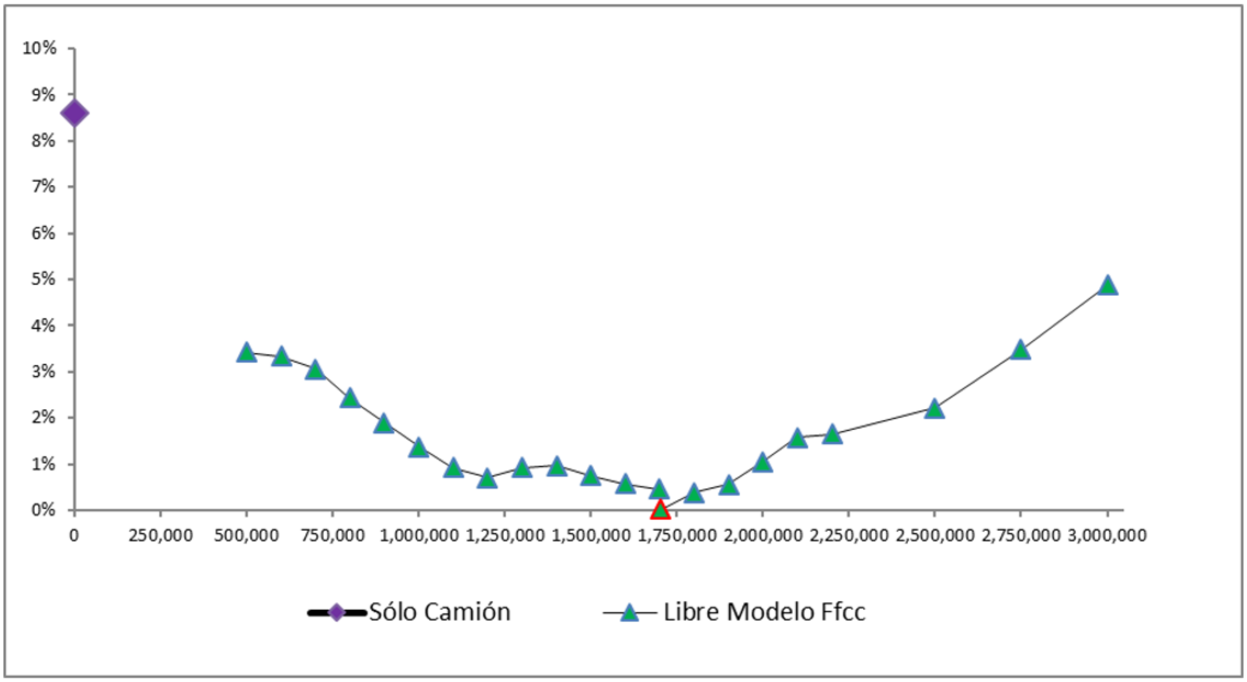


Figure 1.22: Optimal transportation cost scenarios.

Figure 1.23 presents the analysis of unit transport costs in ($ / Ton) of bimodal mode compared against truck-only transport mode ($ 5911 / Ton). The unit cost curves represent the effects of the scale of operation in the case of the train and the shorter truck transport distances as the delivery volumes in bimodal transfer stations increase. However, beginning with the scenarios of 1.7 MM Ton / year the unit costs of the truck begin to rise due to the need to increase the radios of wood supplies to the transfer stations, making the total transport costs less optimal. This situation is reflected in Figure 1.24 where the unit transport costs in terms of $ / Ton_Km increases. Additionally, the optimal rates obtained are compared against the standards indicated in [17].

Figure 1.25 shows the total tonnages associated with each transfer station. The graph shows the tonnage stability associated with the stations farthest from the destinations and the sustained increase in tonnage associated with the station closest to the consumption centers (Lautaro Station) in scenarios greater than 1.7 MM Ton / year.

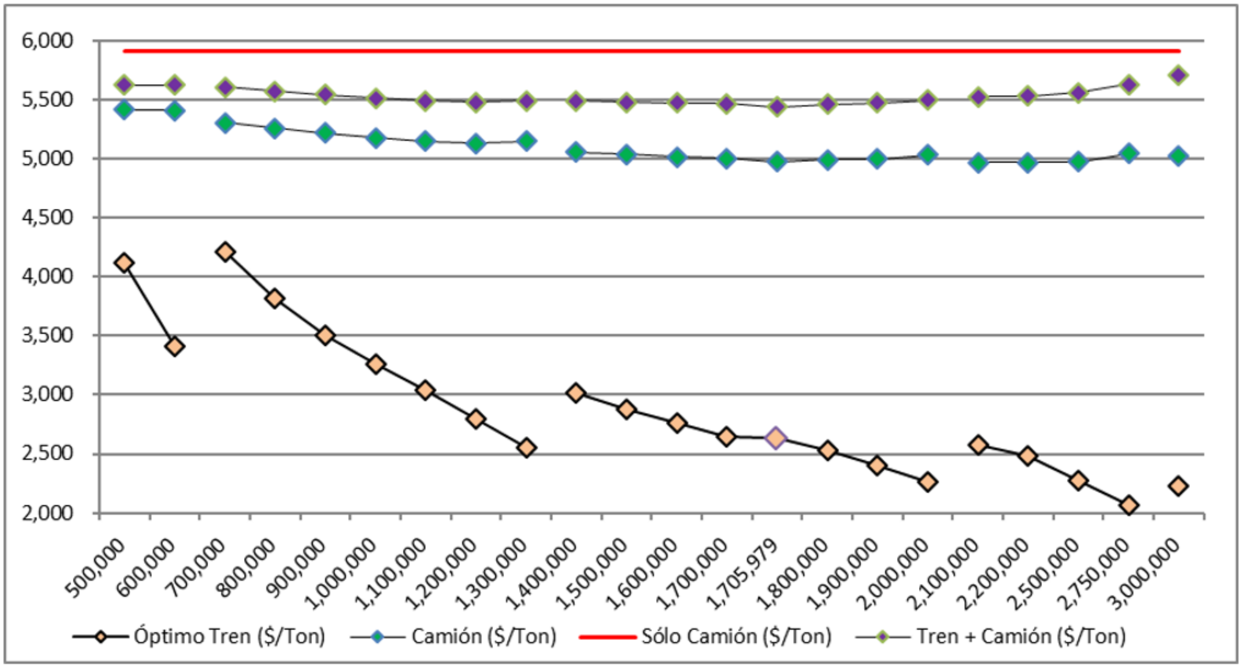


Figure 1.23: Comparison of optimal train cost against truck cost ($/Ton).

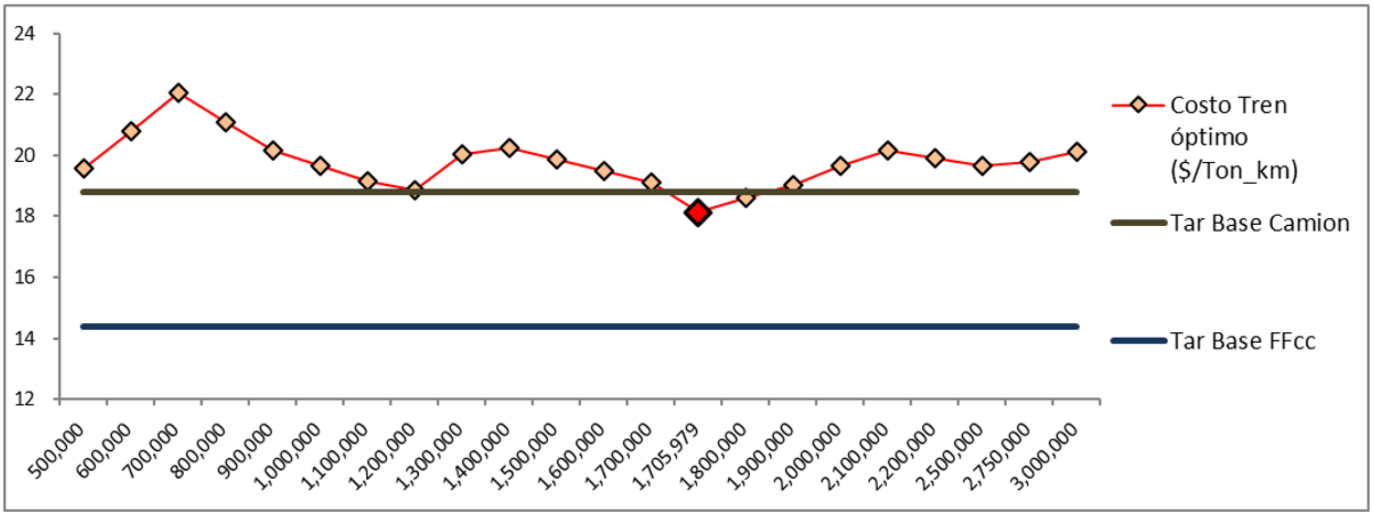


Figure 1.24: Train Transport Unit Cost ($/Ton_km) by scenario.

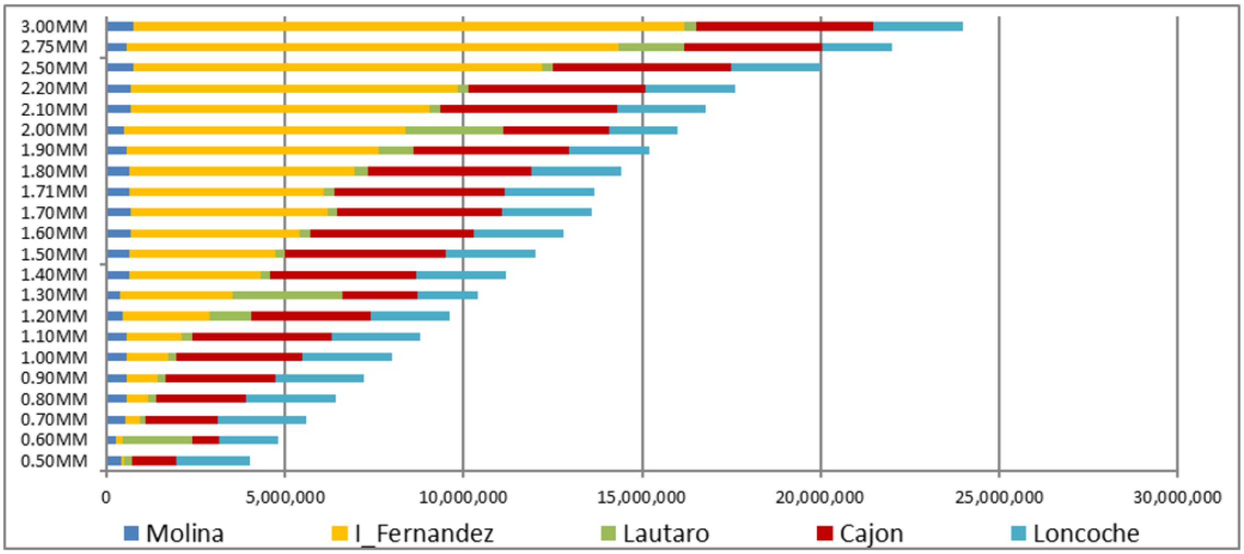


Figure 1.25: Tonnage distribution by transference node.

1.8 Conclusions

This work presents the development and implementation of a mathematical model to solve the problem of strategic planning of the forest products supply chain according to a mixed transport matrix that combines direct trips by truck with trips by bimodal truck-train system.

The application of the proposed model to a real problem had good results obtaining high quality solutions (gap under 0.01%) at very reasonable execution time (10 - 15 minutes), without having to use additional techniques, decompositions or relaxations or heuristic techniques.

The implementation of these developed tools had an important effect on the long-term planning of the company, allowing the bidding of the forest products transport matrix for 8 years and assigning a tonnage greater than 0.7 MM / Ton_year to systems of Rail transport estimating sustainable saving of 1.5% to 2% of the total transport cost of the complete system.

As future work, it is proposed to incorporate congestion management into the model both in the reception of trucks in plants and in the transit of trains.

Chapter 2

Optimization of yarder productivity based on the maximization of cable payload in forestry steep terrain operations

Abstract: *The maximization of cable yarding log payload is a relevant factor to improve forestry productivity levels and achieve competitive costs since it allows to minimize the overall cable operation including operation and setup times.*

We introduce a Bayesian-based optimization heuristic designed to minimize the overall operation time achieved with a standard multi-span yarding system, one of the most commonly configurations in use today, based on an efficient algorithm and accurate new forest inventory models just recently made available at industrial level.

The first field test informs levels of improvements up to 7% under normal operation conditions including setup plus operational working times.

2.1 Introduction and Literature Review

For the next decades, about 50% of Chilean forestry operations will be executed in steep terrains with cable yarding systems. In this scenario, the maximization of cable yarding log payload is crucial to improve forestry productivity levels and achieve competitive costs for this economic sector.

In order to carry out an accurate steep terrain planning process, it is necessary to define an optimal solution for a complex combination of related activities which includes, among others, the optimal location of cable yarding systems, the maximum operation's payload for the cable yarding system, the construction of access roads to the productive area and the transportation of final products to the clients.

During the last two decades, the Chilean forestry area has been using a computational system named PLANEX [15] to support the steep terrain planning process, including road construction and machinery location planning. The system is based on a graphic interactive interface linked to a geographical information system (GIS) storing information on topography, timber availability and geographical barriers like rivers and ravines. The decision process of PLANEX is based on a greedy heuristic. The system has been used successfully, leading to important cost savings as well as better preservation of the environment [25].

Although Planex defines the location of cable landings, it does not define the optimal yarding configuration for each line and do not considers the setup times required for the complete operation.

One of the most commonly used yarding configurations today in Chile is the multi-span yarding system which utilizes intermediate supports to enable "the carriage" to carry a load of logs over a topographic break in slope, condition which otherwise inhibits cable operations since the line would bite into the ground.

There is a big opportunity in optimize the "multi-span" yarding configuration, i.e., the number, size and position of supports in order to maximize the cycle payload. It is also relevant to minimize the overall cable operation including setup times, since cable setup times constitute an important proportion of total costs.

It is a common practice in the Chilean forestry area to use the software LOGGER PC [20] in order to calculate the maximum log payload for each line. Since there are no optimization criteria involved in this calculus, which leaves in the judgment of the operator the yarding configuration, there is a great opportunity in productivity improve by defining the optimal yarding configuration and setup times.

Yarding configuration options depends largely on mechanical analysis of cable systems. As mentioned by Dupire [13], there are two different approaches concerning the mechanical analysis of cable yarding systems. The European traditional method consists of linearized analyses of cable structures [30] while North American one lies on closer to reality non-linear analyses [6] [7]. Although the load path during cable yarding is a dynamic problem, all the existing methods treat it as a static case due to the relatively low speed of the load along the skyline.

According to Dupire [13], the predominant cable system in Europe is known as standing skyline. The skyline is fixed to anchors at both ends implying a constant unstretched skyline length for any load weight and location. The static response to a point load by such cable structures is characterized by the skyline shape and tensile forces change with the load location. It is also important to consider that the cable elasticity also increases the total length of the skyline and also the loaded span length increases by gaining some of the available unloaded adjacent spans cable length [2].

The simplified European method to assess the geometric layout of a cable road is established from linearized analyses of cable structures known as "Pestal Equations" [30] where only the changes in skyline shape are considered. This method leads to shorter spans and more intermediate supports than necessary as shown in previous work [2].

By contrast, under North American non-linear analyses of cable structures approach, they have considered the cable elasticity and changes in shape and tensile forces according to load location. Although these approaches are more realistic, they remain computer-time consuming and by the way are concentrated on single-span cases [13].

Bont and Heinimann [2] developed a complete computer-aided program based on Zweifel's [39] "close-to-catenary" approach for multiple spans configuration which included all the cable responses cited previously. Their algorithm also enables optimizing the intermediate supports locations while respecting predefined safety conditions.

The setup of cable yarder lines is an important part of total costs of a cable yarding operation. Unlike ground-based operations, considerable time is required for rigging a cable line before extraction can begin, as well as taking down the rigging after the extraction is complete. Basic rigging steps include laying out the guylines, preparing the guyline anchors, connecting them and tightening them appropriately. The use of intermediate supports is another specific rigging option that can be employed to extend the terrain range that a yarder can effectively operate. This involves a support jack being rigged into a sturdy tree along the lines that will suspend the skyline above the ground. The use of intermediate supports in cable lines have beneficial effects such that it allows the yarder system to harvest on terrain that is not concave, allows the lines to be extended and allows the logs to remain at least partially suspended as they are being extracted from the stump to the landing. Cable operations are most efficient in larger clearcut operations, where the proportion of rigging time is small compared to the time spent extracting timber. Also, once a yarder is set-up, subsequent lines from the same yarder/landing location can be rigged relatively quickly [34].

A large number of factors influence individual yarder installation times. Line length, terrain factors, extraction direction, and yarder type have been identified as key factors in central Europe. Also, subsequent lines from the same landing location require shorter installation times [34]. Finally, both the number of intermediate support installations as well as the height of the supports are critical factors influencing setup times.

Since last years it has been available LIDAR technologies that recently allows to obtain a census of the forest, describing each one of the trees at each geographic position. Arauco developed a pilot project oriented to evaluate the accuracy and feasibility of semi-automatic forestry census methods, over operational plantations of Pinus radiata [Bustamante, Sandoval]. The pilot considered a LiDAR cloud points of 16 point/m2 and was used to identify trees top height and delineating its crowns width thru a segmentation algorithm. The results obtained allowed us to extrapolate the pilotage area of study an generate an accurate tree census of the harvesting pilot area, obtaining an "individual tree" model based on height of the trees which defines, for every tree in the study area, the position of the tree, the height and the height-diameter relationship, required to evaluate intermedia support feasibility.

Although, several researches had been published in recent years related to cable systems, efforts are still needed in order to develop computerized methods that integrate accurate mathematical approaches for the structural analysis of cable systems. This scientific lack meets the interests of forest operators and managers for an operational and accurate tool for optimizing the setup of cable yarding systems and operating this material in a safe and productive way [13].

Such a tool must contain at least a geographic information system (GIS) based interface to include all the different possible cable locations and directions, a mechanical model to search the optimal layout of intermedia support and cable tensile forces for each potential cable line to insure workers' safety at minimum costs and a location mathematical model to select the optimal set of cable lines that minimizes the whole operation at minimal cost including setup times.

Within the present work and based on previous research we propose a geographic based software tool oriented to fulfill those last objectives. Using results from this software we have test real cable yarding operations for different conditions of steep terrains and forest conditions and have found productivity improvements based on proper setup times and intermedia support selection. Those last results are described in the present paper.

2.2 Problem formulation

In order to examine all possible paths for logging the harvest area and based on tons available for each tree we built a 10 mt. by 10 mt. cell containing all the tons of its associated "individual tree". Each line is associated with a "harvest cone" with its apex been the yarder location and a 50 meters base at the bottom of the harvest area. The cone intersects all the feasible logging cells (see Figure 2.1). Each cell is associated to its nearest "point" at each potential line assuming that the logs are going to be harvested thru this point. (the model does not manage the downhill rolling of logs case). Also, each line is associate with a "Yarding line", a 4 meter's width box along the cable which contains all the intermediate support candidate trees for the line (see Figure 2.1).

The proposed problem looks for a minimum time to complete the whole yarder operation within security conditions and its mathematical model is compound by a network location problem looking to minimize the complete setup & cycle time for all the feasible yarder positions plus a maximization problem for the log load which can be carried out from the farthest point on the skyline to the yarding area while not exceeding the maximum allowable skyline tensions and maintaining adequate log clearance [4].

In order to solve this complete problem, we should be able to solve a large and complex non-linear conditional tension equation system together with an integer location model [4]. Rather than try to solve the problem using traditional nonlinear optimization techniques, due to the potential size and complexity of the model, we propose a two phase technique which, in first term, optimize each potential line independently and then solve the yarder location problem based on each optimal line solution.

In order to solve adequately the problem, it is necessary to run a previous "geometric phase" to offer feasible lines, based on potential yarder locations.

For the "geometric phase" we build a GIS-based tool that draws the lines based on predefined yarder locations. The yarder locations are related to the landing geographic position defined by the PLANEX solution [15]. For each landing position, we define a series of poten-

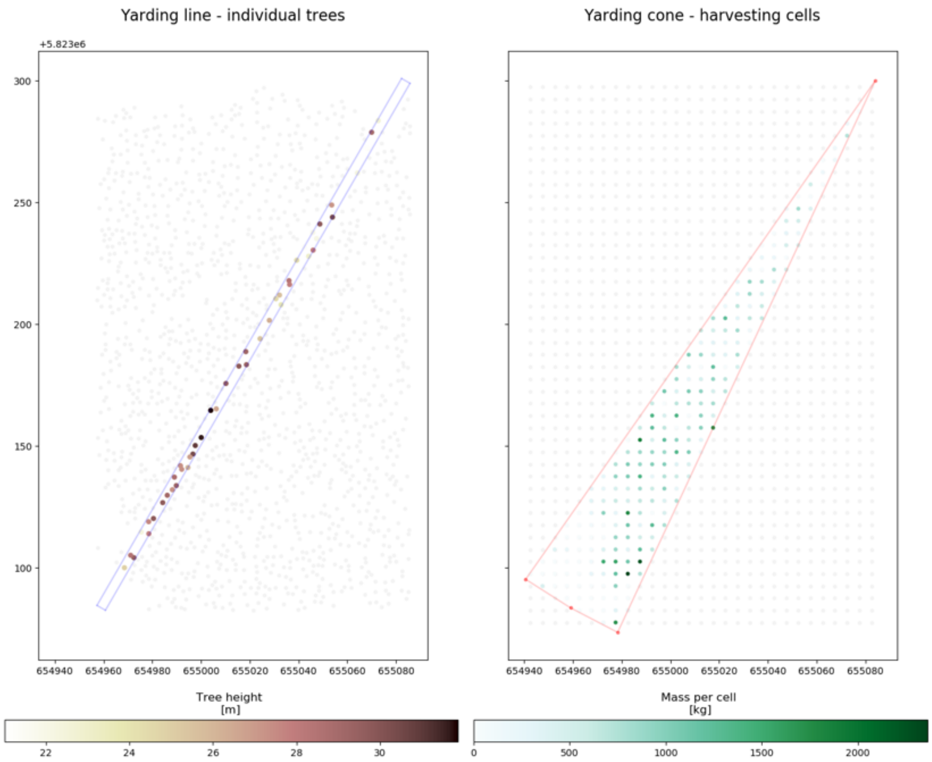


Figure 2.1: Yarding line & cone.

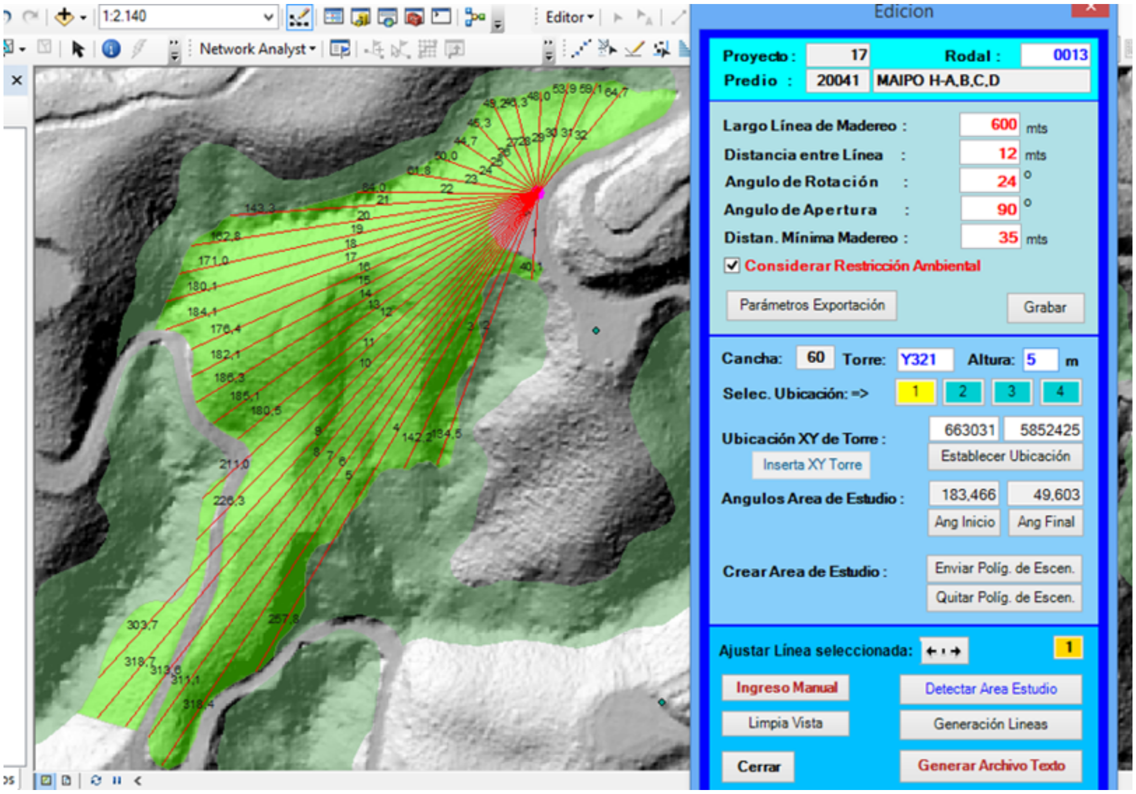
tial yarder locations separated along the landing.

Each yarder locations defines a fan of lines over the harvesting area (see Figure 2.2). The GIS tool eliminates unfeasible lines based on terrain slopes. Since the "line cones" are big enough we drawn the line closer to each other, so the cones got overlapped allowing a bunch of feasible solutions. The geometric phase draws all the feasible lines taking into account the requirement of full harvesting area coverage, the harvesting area limits and environmental restrictions. Each line has to be feasible, which means that depending on the composition of slopes present thru the line, the skyline should be able to "run" completely thru it, otherwise it is eliminated from the solution set (see Figure 2.3).

Since the shape of the harvest area is normally highly irregular as well as the distribution of mass in between cells, together with the bounded availability of yarder locations based on roads dispositions, the geometric phase should offer enough lines to make feasible the complete harvest of all the cells.

The problem of optimizing intermedia support has been largely solved by intuition or trial and error by the years [3], mainly by some rules of thumbs proposed by [30].

Chung proposed an automatic procedure to locate intermedia support based on firstly installing intermedia support on all protruding profile points and then eliminate the second of three consecutive intermedia support. The procedure iterates until a termination condition is met but without optimality proofs [8].



Edicion

Proyecto : 17 Rodal : 0013

Predio : 20041 MAIPO H-A,B,C,D

Largo Línea de Madereo : 600 mts

Distancia entre Línea : 12 mts

Angulo de Rotación : 24 °

Angulo de Apertura : 90 °

Distan. Mínima Madereo : 35 mts

☑ Considerar Restricción Ambiental

Cancha: 60 Torre: Y321 Altura: 5 m

Selec. Ubicación: => 1 2 3 4

Ubicación XY de Torre : 663031 5852425

Angulos Area de Estudio : 183,466 49,603

Crear Area de Estudio :

Ajustar Línea seleccionada: 1

Figure 2.2: Geometric phase.

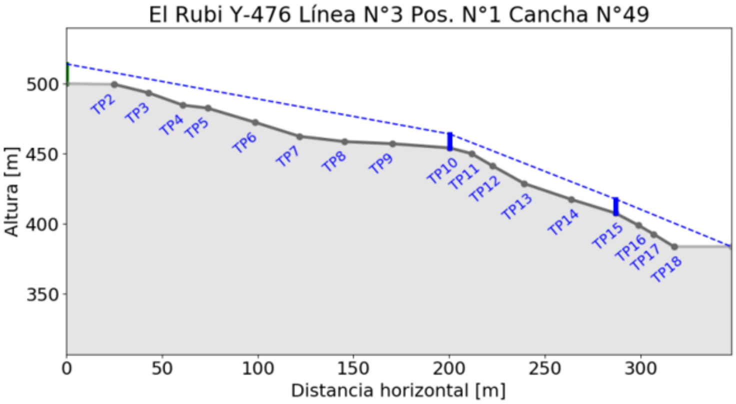


Figure 2.3: Feasible line.

Leitner proposed an optimal intermedia support location and height [26]. However, the model did not take into account a minimal ground clearance.

Bont developed an optimal intermedia support location and height model based on close to catenary cable mechanics [3]. However, the model does not take into account the existence on actual trees near the selected intermedia support location.

Based on previous work we develop a maximum "log load algorithm" for each feasible line with the following steps:

1. Define a descending list of {max loads} from 3 Tons to 1.5 Tons.
2. Define an ordered list of {support-type configurations}, been the first one, no intermedia support & "tail in stump", the second one, no intermedia support & "tail in support", the third one intermedia support & "tail in stump", and so on, been the last one 3 intermedia support & "tail in support".
3. For each combination of {max load} & {support-type conf.}
    (a) For each {intermedia support location} in the line identify all support trees in the "Yarding line" and select the feasible ones.
    (b) Evaluate all the combination {feasible intermedia support location, quantity of intermedia support, height} using the Skyline XL tension equations and calculate the maximum log load as the objective function.
4. Once evaluated all combinations, select the maximum load achieved

During the "log load algorithm" when evaluating phase (3.b) and given that the selection of the optimal log load must be performed by the extremely computational expensive tension equations, we implemented a Bayesian Optimization method since it has been successfully used to optimize complex black-box functions whose evaluations are expensive [21][33]. The Bayesian Optimization method allows us to evaluate all the combination of intermediate support positions in order to maximize the log load of each feasible line.

The basic tension equations were developed by Kendrick [24] and are implemented in Skyline XI. Skyline Xl was developed by the Oregon State University and the Oregon State Forest Service and accepted worldwide as a tool to get the maximum tension for cable operations calculus.

We took Skyline Xl and treat it as a "black box" to evaluate maximum cable tensions.

Finally, in the last step of the optimization process we minimize the setup & cycle times for all the feasible lines defined using a mixed-integer optimization model and the results of the second step optimization as the cycle time for each line. The output of the Bayesian Optimization method works as an input for the mathematical model that minimizes the overall operation.

As the feasible lines must be close enough to each other, in order to cover all the cells, the harvest cone of different lines overlap each other, and the optimization process must select in between several adjacent lines. Based on this main idea and in order to harvest each cell one and only one time we introduce the concept of over-distance logging, in which the line will harvest cells beyond his “harvest cone” with an extra time: this “overlogging” option is a commonly used operational solution for this problem. As the amount of “over-distance” can be a big operational problem that has to be controlled, the model only allows the “overlogging” of a reduced number of cells.

In order to implement the latter conditions, the model selects optimal lines that harvest all their associated cells and allows to harvest over-logged cells near to optimal lines.

Additionally, some operational restrictions have to be implemented. As mentioned earlier, there are environmental restrictions that prevents logging over certain areas. In our solution, the “geometric phase” takes into account this condition and restrict potential lines that logs over protected areas.

Also, operational rules restrict the crossing of logging lines even if it is optimal. In order to implement this restriction, we calculate and restrict all the combinations of lines that violates this restriction.

Mathematical Model

Sets

I	Cells to be harvested
J	Potential yarder installation points
L	Potential lines
L_j	Set of lines associated to installation point j
I_l	Cell to be harvested optimally using line l
I'_l	Cell to be harvested non optimally using line l
L_{i}	Line l that harvest optimally cell i
L'_{i}	Line l that harvest non optimally cell i
R_l	Set of all lines that violates the crossing restriction for line l

Parameters

f_j	Instalation time for position j
n_l^j	Instalation time for line l for position j
c_l^{i}	Logging time for cell i using line l optimally
c'^{i}_l	Logging time for cell i using line l non optimally
v_{i}	Total mass available on cell i
q_l	Total quantity of cell feasible to be harvested optimally by line l

Variables

$Xo_{\mathrm{i}l}$	Indicates 1 if cell i is logged optimally thru line l
$Xs_{\mathrm{i}l}$	Indicates 1 if cell i is logged non optimally thru line l
Y_{i}	Indicates 1 if cell i is logged optimally
T_j	Indicates 1 if location point j is activated
Lo_l	Indicates 1 if line l logs optimally

Objective function

$$Min z = \sum_{j\in J} T_j * f_j + \sum_{j\in J}\sum_{l\in L_j} Lo_l * n_l^j + \sum_{j\in J}\sum_{l\in L_j}\sum_{\mathrm{i}\in I_l} Xo_{\mathrm{i}l} * c_l^{\mathrm{i}} + \sum_{j\in J}\sum_{l\in L_j}\sum_{\mathrm{i}\in I'_l} Xs_{\mathrm{i}l} * c'^{\mathrm{i}}_l$$

Restrictions

$$Y_{\mathrm{i}} >= 1 \qquad \forall \mathrm{i} \tag{2.1}$$

$$y_{\mathrm{i}} - \sum_{l\in L_{\mathrm{i}}} Xo_{\mathrm{i}l} - \sum_{l\in L'_{\mathrm{i}}} Xs_{\mathrm{i}l} = 0 \qquad \forall \mathrm{i} \tag{2.2}$$

$$\sum_{\mathrm{i}\in I_l} Xo_{\mathrm{i}l} - q_l * lo_l = 0 \qquad \forall l \tag{2.3}$$

$$lo_l - BigK * \sum_{k\in R_l} lo_k <= 0 \qquad \forall l \tag{2.4}$$

$$\sum_{l\in L_j} lo_l - BIGj * t_j <= 0 \qquad \forall l \tag{2.5}$$

$$y_{\mathrm{i}}\ ,\ xo_{\mathrm{i}k}\ ,\ xs_{\mathrm{i}k}\ ,\ lo_k\ ,\ t_j\ binary$$

The objective function minimizes the logging time of cells optimally logged plus the logging time of cells "over-logged" plus the setup times for lines plus the installation time of yarders in the different positions. Restriction (2.1) obligates to harvest all cells. Restriction (2.2) obligates to harvest a cell thru an optimal line 1 or as an over-logged cell using a non-optimal c'^{i}_l harvest time. Restriction (2.3) activates an optimal line l only when all its associated optimal cells are activated. Restriction (2.4) restricts the activation of optimal lines that violates the "crossing line" condition. Restriction (2.5) activates the installation of a yarder in position j when at least one line associated to position j is activated.

2.3 Implementation & results

The Geometric phase is implemented over an ESRI ArcGIS graphical environment and allows the user to define the landing location, all the alternative tower positions, environmental restrictive polygons and parameters for the definition of potential lines, such as distance in between lines, logging distance and cone width.

The Bayesian Optimization's first step of the model is implemented on a Python 3.0 environment and solve a landing in a variable amount of time that goes from 15 minutes to 17 hours depending on the complexity of the terrain conditions and the number of lines.

The MIP Mathematical location's optimization procedure is implemented in GAMS 24.9 that runs under CPLEX 12.7.1, in a 64 bits Windows System on an Intel Xeon 2 Server with 156 GB RAM.

Once the two steps on the algorithm are finished, a digital report is sent back to the geometric phase and a graphical view of the result is presented to the final user. This final report includes the graphical view of the selected lines, the maximum log load of each line at each point and the cells covered by the solution.

As traditional planning of lines tends to define an exit support for the line in its first 20 meters, the proposed solution tends to define higher log loads for the lines increasing the overall productivity of the team. Additionally, as the model is very strict in complying with technical, security and environmental restrictions, it generates solutions that are more friendly with the environment and safer.

We test the proposed methodology for 5 landing positions in the study area. For each landing, where the initial position of the tower was defined by operational crew, we calculate and compare the optimal line configuration against the traditional operational solution. The traditional operational solution is normally build using the "LoggerPc" tool in a later field validation.

We use a standard function to calculate time for each solution as a way to compare the quality between them. We have compared the optimal versus the traditional solution for each landing considering the complete operation including setup operational times.

2.3.1 Preparation of input data

The software has been tested in one of the operational areas of Forestal Arauco located in Llico, Arauco, eight Region, Chile. The test included Radiata Pine stands whose characteristics are shown in Table 2.1, while the team characteristics are described in Table 2.2.

Size of the stand (ha)	40
Age of the stands (Years)	21
Density of the stands (Tree/ha)	1300
Average height of the stand (m)	26
Average volume by tree (m3/tree)	0.5
Average volume by stand (m3/ha)	600

Table 2.1: Test area characteristics.

Harvesting mode	Full tree
Felling mode	Traditional (manual chainsaw)
Logging mode	Cable using multispan skyline
Processing mode	Processor
Yarder Height (m)	14
Number of Anchor	5

Table 2.2: Test team characteristics.

For the sake of the study we got land use maps including environmental restrictions and plantations, planned area maps including harvesting areas, roads and landing locations and DEM (Digital Elevation Model) LIDAR based maps. The base info is separated geographically into independent "Landings" based on landing locations and harvest area associated.

We also prepared an "Individual tree" model layer for each "Landing" based on [Bustamante, Sandoval]. Thru the "Individual tree" model available por each "Landing" we can recover, for each tree, its position and total height and estimate Diameter at Breast Height (DBH) and Height-Diameter relationship. And each "Landing" is incorporated to an ARCGIS application that builds the data entry for the model.

From Arauco's official productivity systems we recovered, for the specific team been tested, the average time of the operational cycle at different extract distances and slope conditions. We also recovered average setup times including installation times for the yarder, change of line average times (new line) and intermedia support installation time.

From the planned area maps we got each landing zone. Since the landing zone is represented by a single dot in the map, we replace each dot by a 900 square meters (50 x 18 meters) rectangle shaped around the road representing the full "Landing zone". Each "Landing zone" is drawn along the road and centered around the original dot and allows the installation of five different locations for the yarder. We define 5 different locations for the yarder in each landing (1 position every ten meters along the landing)

On each Yarder location it is possible to define subsequent lines that require shorter installation times. Depending on the size of the harvesting area, and for each yarder location, we define as many consecutive lines as possible to cover the complete harvesting area. Each line is defined by a yarder location point and an azimuth direction which defines the course of the line. Each line defines a 5-meters sequence potential intermedia support points.

From de "individual tree" model it is possible to, thru a LIDAR based tree height measure, adjust with high accuracy a height-diameter model to any tree in the harvest area [10] [19] [18] [12] [32]. Using the height-diameter relationship it is possible to define "candidate trees for intermedia support" at different locations throughout the line.

From the "individual tree" model it is possible to estimate the volume of wood available on each point of the harvest area [10] [19] [18] [12] [32]. Using standard density (Kg/M3) functions we calculate available tons to carry out of the harvest area.

2.3.2 Numerical results

We test the model for the landing number 36 in the study area. We recovered the lines defined in fields by experts (landing direction, length and number and position of intermedia supports) and we compare them against the optimally defined lines defined by our system.

For the sake of a valid comparation, to calculate setup times, we the standard for "Tower installation times" and "intermedia support installation times" for the specific team. Also, as the "traditional" solution does not consider any tree model, we associated the LIDAR based "individual tree model" to the "traditionally" defined lines and used it to calculate operational times, based on max load defined by operators.

In this case, the model optimally selected lines 5, 10, 14 21 and 29, as shown in Figure 2.4.

Figure 2.5 shows the profile of one the five selected lines by the mathematical model that minimizes the total operational plus setup times.

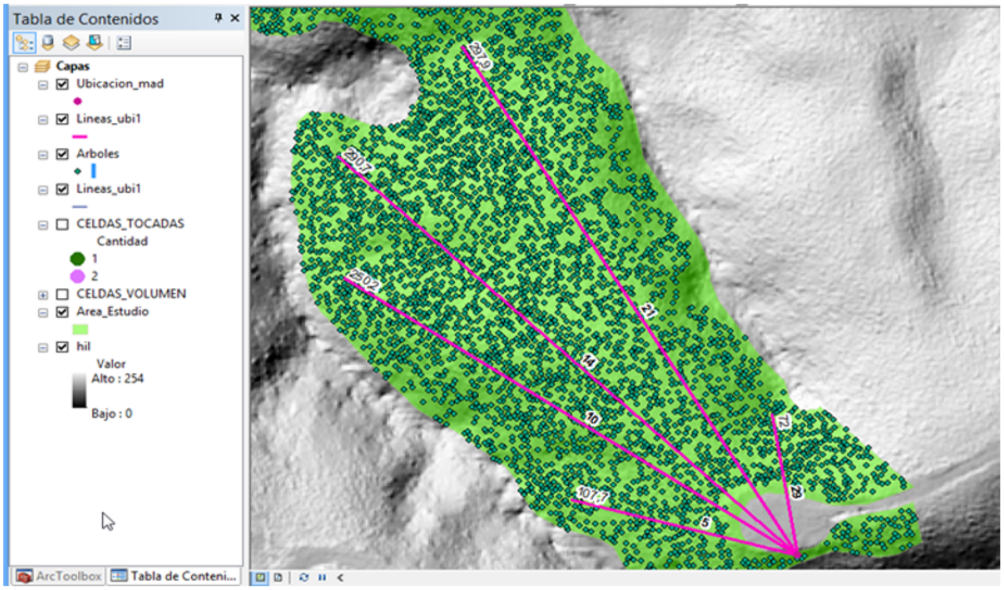


Figure 2.4: Lines selected.

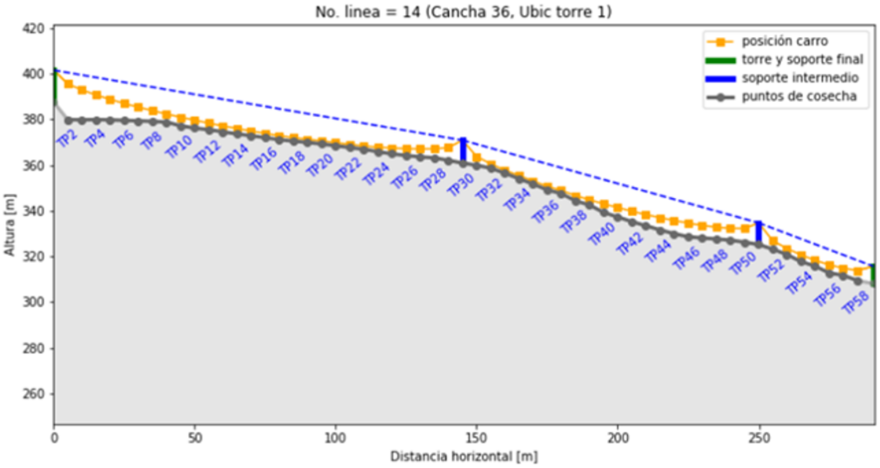


Figure 2.5: Profile for selected lines.

Then, we compare the optimally defined lines against traditionally defined. As observed in Figure 2.6, the traditional crew selected lines 15 and 19 instead of lines 14 and 21.

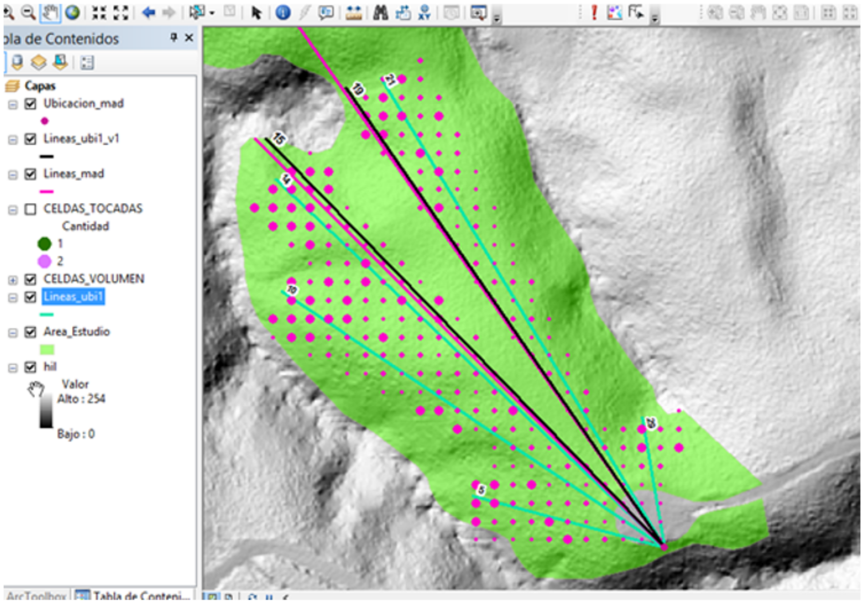
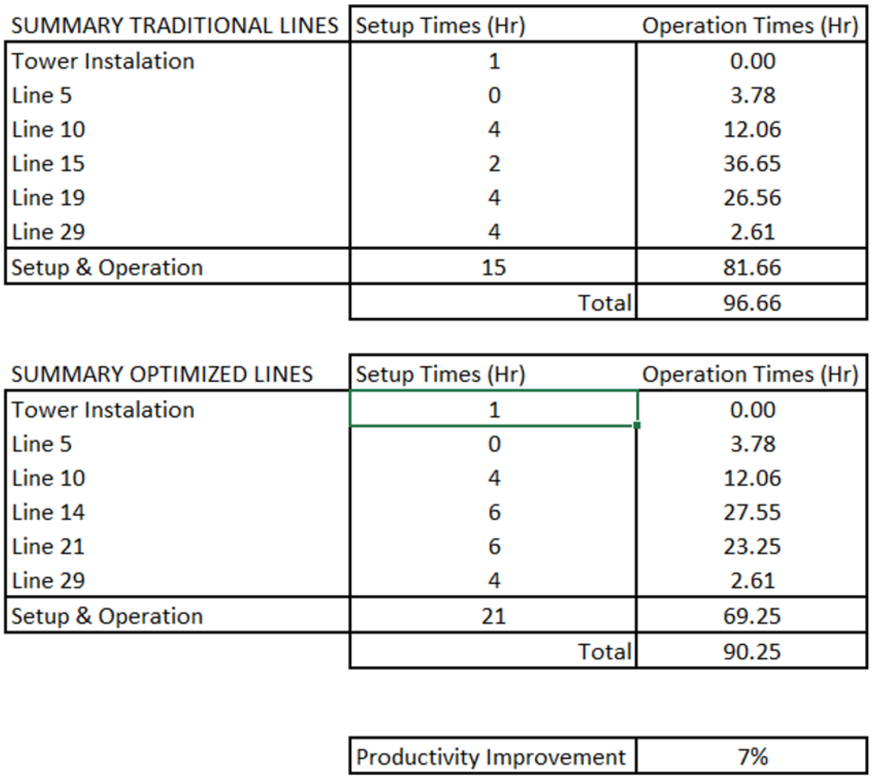


Figure 2.6: Comparison of traditional versus system selection of lines.

The traditional method selected lower setup-time lines but slower in operation speed. Al the end, when considering the overall productivity time, the inclusion of more complex lines gave a better productivity condition due to faster overall operation times. Finally, Table 2.3 present a summary of total times for the complete harvesting of landing 36.



SUMMARY TRADITIONAL LINES	Setup Times (Hr)	Operation Times (Hr)
Tower Instalation	1	0.00
Line 5	0	3.78
Line 10	4	12.06
Line 15	2	36.65
Line 19	4	26.56
Line 29	4	2.61
Setup & Operation	15	81.66
	Total	96.66

SUMMARY OPTIMIZED LINES	Setup Times (Hr)	Operation Times (Hr)
Tower Instalation	1	0.00
Line 5	0	3.78
Line 10	4	12.06
Line 14	6	27.55
Line 21	6	23.25
Line 29	4	2.61
Setup & Operation	21	69.25
	Total	90.25

Productivity Improvement	7%

Table 2.3: Summary results of landing 36.

When we compare the total operational plus setup times for the landing using the traditionally defined lines against the optimally defined lines, we obtain 7% of productivity improvement.

2.4 Conclusions

The results obtained showed that based on LIDAR technology it is possible to build a tree census of the harvesting pilot area, obtaining an "individual tree" model that allow us to evaluate intermedia support feasibility. Based on terrain experience it is possible to identify in fields the intermedia support candidates to maximize log load capacity.

Even though the two-step model generates accurate solutions to harvest accurately the study area, still the line Bayesian-based optimization step is highly time consuming taking a bunch of time in difficult cases. By example, a complex landing area may take up to 17 to 20 hours to process.

Although the main aspects related to the preparation of harvesting projects considers the location of machinery and the design of access roads, functions that areas completely covered by Planex, it is also of vital importance the definition of log lines that maximize the log load capacity oriented to achieve productivity increase in steep terrain zones.

This paper presents a heuristic approach that supports the latter decisions and has been tested successfully in a pilot area in Chile and that successfully combines operation research techniques and geographic information techniques in a computational solution that impacts the forest operation planning process.

Despite the individual tree model showed accurate results to identify intermedia support candidates, in the case of high-density forests, i.e., forest with more than 700 trees by hectare, it became difficult to identify individual trees in the forest. For such cases we propose a static based methodology instead of an individual tree model. Such methodology must expect the existence of a certain quantity of candidate trees in a specific area near the line.

Although the model returns adequate results for intermedia support solutions, it may take a lot of time, mainly in the first step of the process. One option to minimize the excessive amount of processing time is to evaluate each line just in the changes of slope, instead of every 5 meters, just as it happens in Logger Pc traditional operations.

The application of the model in real operational conditions gave us a direct improvement of 7% in productivity versus traditional method for the study area. The next step of the project will consider the comparison of all the remaining landings in the study area (approximately five landings).

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