OPTIMIZING THE ENAP’S SYSTEMS FOR DISTRIBUTING Refined PETROLEUM PRODUCTS BY TANKERS AND PIPELINES

TESIS PARA OPTAR AL GRADO DE DOCTOR EN SISTEMAS DE INGENIERÍA

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Esta tesis está compuesta de dos trabajos de investigación aplicados desarrollados en la Empresa Nacional del Petróleo, ENAP.

En la primera parte de esta tesis presentamos un enfoque de optimización para determinar la programación óptima de la flota de buques que distribuyen productos derivados del petróleo en Chile. El proceso de programación de la flota se preocupa de la distribución de diferentes productos a diferentes clientes distribuidores minimizando el costo total. Estos clientes tienen distintas capacidades de almacenamiento y están localizados en los puertos de todo el país. El modelo de optimización construido es un modelo exacto, basado en la definición de cada arco recorrido por cada buque en cada viaje. Sin embargo, es un modelo MIP de gran tamaño que no fue posible de resolver usando un paquete comercial (Modelo de Nodos). Dado lo anterior, generamos un modelo aproximado basado en un conjunto de rutas factibles completas para cada buque. Este nuevo modelo resultó más manejable y provee buenas soluciones factibles (Modelo de Rutas). La mejor solución del modelo de rutas se utiliza como solución factible inicial para el modelo de nodos, permitiendo la solución de este último con un muy bajo gap residual y en tiempos razonables de cálculo. Este enfoque de solución de dos etapas ha sido usado en ENAP desde 2015 y los usuarios cuentan con una amigable interfaz gráfica conectada con el motor de optimización. Este nuevo sistema reemplazó al tradicional enfoque manual y ha permitido ahorros en costos operacionales en el orden de 9%.

En la segunda parte de este trabajo descriptamos la creación, desarrollo e implementación de un sistema de distribución de productos derivados del petróleo vía oleoductos en ENAP. La programación del oleoducto se realizaba en forma manual, basada en la experiencia y en la necesidad de satisfacer restricciones físicas del oleoducto, restricciones operativas de la refinería y satisfacer demanda de clientes. La complejidad de este problema y la necesidad de reducir costos operativos sugirió la creación de un modelo de optimización, basado en programación entera. El resultado positivo del proyecto se debe en forma significativa a la constante interacción con los programadores y el equipo de optimización. Los comentarios precisos de los programadores permitieron limitar la complejidad del modelo. El sistema resultante es fácil de usar para los programadores gracias a un amigable interfaz usuario, y su solución requiere poco tiempo computacional. Este modelo es usado una vez al mes para planificar la operación mensual y permite presentar a los clientes distribuidores las fechas y volúmenes que recibirán de cada producto. Los ahorros en costos operacionales del oleoducto son del orden de 10%.
This thesis is composed by two research projects developed at Empresa Nacional del Petroleo, ENAP.

In the first part of this thesis we present an optimization framework for determining the optimal schedule for a fleet of tankers delivering refined petroleum products for ENAP, a state-owned company in Chile. The scheduling process addresses the distribution task of satisfying the demand for multiple products to multiple clients while minimizing the overall cost. These clients have different storage capacities and are located near ports along the coast. The optimization model is an exact one, based on defining each leg of each trip for each tanker. It was however a very large scale MIP model unsolvable using a commercial code (Node Model). We generated an approximate model based on a set of feasible routes for each tanker. This model makes the problem more tractable and provides good feasible solutions (Routes model). The best solution is used as a hot start for the original Node Model, allowing its solution with very low residual gaps in moderate computer times. This two-step approach was implemented and has been used at ENAP since 2015. A graphical user interface provides a friendly format for the schedulers. The new system replaces the manual process that was used in the past. It has been a milestone change at ENAP and it is currently saving 8-9% of the total operational cost for the maritime distribution system.

In the second part of this work we describe the creation, development, implementation and impact of a system optimizing the distribution of petroleum products by pipeline at ENAP. Scheduling used to be done by hand, based on experience and on the need to satisfy physical constraints in the pipeline, supply constraints in and out of the refinery and demand constraints from clients. The complexity of the problem and the need to cut down on operating costs suggested turning to optimization, specifically integer programming. The positive results of the project owe a lot to the constant interaction between schedulers, deciders, and the optimization team, and to the insights provided by the schedulers that allowed to limit the model’s complexity. The resulting system is easy to use for schedulers thanks to a graphical user interface (GUI), and its solution requires little computer time. It is used once a month for planning the next month operations and negotiating delivery dates and amounts with the clients based on the solution suggested by the model. Operating cost savings are of the order of 10%. The system has also been used to evaluate an alternative distribution approach.
A mis queridos Mar-Mar: Maru y Mariano
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Introduction

In the oil and gas industry the distribution of refined oil products is a critical component of the supply chain. The first part of this apply research addresses the problem of optimizing the schedule of a multi product pipeline that transports 6 types of refined oil products from the refinery to multiple demand points along the pipeline. The size and contents of each batch injected at the origin should be determined taking into account its arrival times at the demand points and the volume each client is going to take from it. Since there is no physical separation between consecutive products, in the vicinity of their contact surface consecutive products mix. These mixes are collected at the end of the pipeline for reprocessing. The combinatorial nature of the problem suggests the use of MIP techniques. Based on chemical and operational constraints for the refined oil products, we create a set of feasible sequences, linear arrays of products, to inject in the pipeline. The model decide which type of sequences to use, in which order and the volume of each batch of them in order to minimize the overall operating and reprocessing cost. The model is currently used at ENAP with successful economical and operational results for the state owned Chilean company.

In the second part of this work we present an optimization framework for determining the optimal schedule for a fleet of tankers delivering refined petroleum for ENAP. The scheduling process addresses the distribution task for satisfying the demand of multiple products by multiple clients, with different storage capacities, and located near ports along the coast country, minimizing the overall cost. The optimization model built was a large scale MIP mode and was unsolvable on CPLEX (Nodes Model). So, a new model based on a set of feasible routes per vessel was generated making the problem more tractable and providing feasible solutions (Routes model). These solutions were used as starting ones in the original MIP model, allowing to solve it with very low residual gap. This 2 steps approach was implemented at ENAP through a friendly GUI for the schedulers and replaced the manual process that was done for years in the company. It is been a milestone change at ENAP and is currently saving 8-10% of the total operational cost.
Chapter 1

ENAP’s optimization system for distributing refined petroleum products by tanker

1.1 Introduction

This paper presents a system developed and implemented for ENAP (Empresa Nacional del Petroleo) to schedule product delivery by tankers for cities in the northern and southern regions of Chile. ENAP is the state-owned petroleum company in Chile that plays a key role in the national energy portfolio. It carries out oil and gas exploration and production in Chile and other countries. Its main business is transforming crude oil into refined products. The fuel market structure in Chile is characterized by the presence of ENAP as the main fuel wholesaler. ENAP does not participate in the retail business; and three distributors (Copec 60%, Enex 24% and Petrobras 12%) concentrate 96% of the country fuel sales. The remaining 4% correspond to small distributors that totally depend on ENAP for their fuel supply.

ENAP is the single crude oil refiner in Chile and imports 98% of its crude. In South America this crude oil comes mainly from Ecuador, Argentina, Brazil, Colombia and Peru. Outside the American continent it comes from West Africa and the North Sea. Only 2% of the Chilean crude oil demand is supplied from ENAP’s oil fields, which are located in Magallanes (southern part of the country). Overall the crude oil refined by ENAP allows the company to deliver 65% of the country fuel demand, the remaining 35% being fulfilled by already refined fuel imports procured by both ENAP and other distributors. Fuel supply represents 45% of the total energy demand in Chile, the remainder is fulfilled by liquified natural gas (12%), coal (16%), hydraulic generation (17%) and other sources of energy like wood or solar (10%).

Due to state regulations ENAP utilizes a fuel market price equilibrium based on a fuel import parity price from the US Gulf Coast (USGC), as the nearest, biggest and most liquid fuel market. That is, the price of a fuel in a port in Chile should basically mimic the price of
the same fuel in USGC plus the transportation cost from there to that port and other minor fees related with customs and insurance.

The transformation of crude oil into end products is carried out in two refineries, Aconcagua and BioBio, located in the center and south of Chile. Each refinery is connected with its respective port through a pipeline. In particular the Aconcagua refinery is besides the port of ConCon, so that the crude oil unloaded in ConCon can be transported to the Aconcagua Refinery. The main products coming out of the refineries are 93 octane gasoline, 97 octane gasoline, diesel, fuel oil and domestic kerosene. ENAP also imports refined products to satisfy part of the demand. There is a third very small port in Punta Arenas, the southernmost city in Chile to cover the small demand of that region.

Chilean geography is extremely diverse with a very unique, long and thin, shape. From North to South, Chile extends 4,270 km (2,653 miles), and yet it only averages 177 km (110 miles) east to west, with most of the population and industries settled between two mountain chains (Andes and Costa) that go from the North to the South. About 68% of fuel demand is concentrated between Santiago and Concepcion (VIII region in the south), thus ENAP’s refineries are positioned in the strongest demand areas. Because of its geography, transporting fuel by trucks is expensive. Also, connectivity can be endangered by disruptions such as bad weather or earthquakes. Demand in cities between San Vicente and Santiago is fulfilled through a pipeline that joins San Vicente and Maipu, a distribution center near Santiago. The rest of the regions to the North of ConCon and the south of San Vicente are supplied mainly by tankers.

In terms of the literature, to the authors knowledge, the research done in the field of fuel refilling by tanker is very limited and has not been studied in the OR community. There is plenty of research done on containership scheduling (see [3]). However, the problem of optimizing distribution of petroleum products by tankers has not been studied in depth. A good review of the research in maritime transportation planning is [1].

1.2 The tankers distribution system at ENAP

Given the fact that refined products are needed for industries like mining, public and private transportation and others, the distribution function that ENAP performs in Chile is critical. This is particularly relevant for a state owned company. In commercial terms, the company runs annual contracts with its clients, in which demand is defined in monthly volumes with some tolerance and both players have rights and obligations. The main factors that drive the distribution policies are: a) the volume should be delivered on time and in the right amounts,b) the products must satisfy defined chemical specifications. On average, ENAP’s overall monthly demand is approximately 900,000 m3, one third of them being distributed by tankers.

As mentioned above the Chilean territory is a long and thin portion of land, see Figure 1.1. North of ConCon and South of San Vicente, petroleum products are distributed by tankers. In the maritime system there are 3 loading ports located close to the refineries,
named Quintero (Q0), San Vicente (SV0) and Gregorio (a small port) and 15 unloading ones. In each unloading port ENAP delivers up to six petroleum products to the three already mentioned main distributors.

Figure 1.1 illustrates the shape of the country, and the port locations. It also illustrates one possible route a ships can take going north of ConCon in red color. It starts loading in Quintero (Q), then delivers in Arica (1) as first port, then Mejillones (4) as second port, then Barquito (6), then Guayacan (8) and, finally returns to Quintero to ends the trip and start loading for the next one. In blue color is a route starting at San Vicente and visits Chacabuco, Pta Arenas which then returns to San Vicente.
ENAP schedulers used to perform the scheduling process through a manual procedure that basically mimics a monthly pattern that has shown to work reasonably for a long time. They then make small changes to adapt the schedule to particular requirements. The Logistics Department at ENAP realized that perhaps there was a way to do the scheduling task more efficiently and contacted the head of the Operations Research Division within the company (one of the authors in this paper) which gave birth to the work described in this paper.
1.3 Description of the two models

Taking into account the supply network described above, we developed an optimization model to address the task of running the petroleum products distribution system at minimum cost. Such a model should capture the key elements of the supply chain, starting at the storage tanks of end products at the refineries to the delivery points to distributors along the established routes. The model must satisfy the most relevant operational and commercial constraints such as meeting the demands of customers, respecting capacities of the stowing configurations, satisfying the time windows for visiting each port. An optimization model for running the tanker operations was developed.

One feature of the petroleum tankers that make this problem more complex is that each tanker has a set of compartments for storing products below deck, which are not visible from the outside. For clarity of the explanation in Figure 1.2 we first provide an outside view of a tanker:

![Outside view of a petroleum tanker](image)

*Figure 1.2: Outside view of a petroleum tanker*

On the other hand, Figure 1.3 provides a schematic aerial view of the internal compartments setup, and two feasible assignments for the products inside, which are called stowing configurations. For each trip a stowing configuration should be defined and, in case it changes from the one selected in the previous trip, some compartments must be cleaned using high pressure hoses.

![Two different stowing configurations](image)

*Figure 1.3: Two different stowing configurations*
Given a monthly demand in cubic meters the decisions that the optimization model should take include: the scheduling for each trip of each tanker of the fleet, the stowing configuration, the volume of each product to be loaded in loading ports, the volume of each product to be unloaded in each demand port, so as to minimize the total cost. The combinatorial nature of the decisions that must be made can be modeled using MIP techniques, resulting in a large scale model.

**Node Model (NM)**

For the problem described above the first MIP model built was very detailed and looked for feasible trips on the fly, that is, for each trip of each tanker from a particular unloading port, the model was deciding which port to visit next having all the network available. We call this formulation *Node Model*. Based on this setting the size of the model was too big and the first attempts of running the full tanker-routing model straight on GAMS-CPLEX were not very promising. As an example, an instance of the model ran for more than 20 hours on an Core i7 with 8GB RAM and a 2.4 GHz processor without returning any feasible solution. Moreover, CPLEX returned an 'out of memory’ message, mainly because the size of the tree in the branch and bound was reaching dozens of gigabytes.

**Route Model (RM)**

As a way to build a more tractable formulation, and based on a in-depth knowledge of the operational problem, we thought of providing full routes to the trips. That is, for each tanker, we created a list of meaningful feasible routes. We called this formulation *Routes model*. This approach worked very well and dramatically reduced the size of the model.

As a consequence, we were able to find feasible solutions in 20 mins with residual gaps of 5-7% in the branch and bound process. We used these solutions as hot starts to run the NM and getting a much better solution on this last one. In the next section we describe the mathematical formulation of the Node Model.

It is important to emphasize that a column generation scheme might have been a solution approach for NM. However, this approach would be extremely difficult to implement as decisions in the subproblem involve not only a route for a ship in a trip, but also a detailed stowing configuration and the volume of each product delivered at each port. Given these difficulties we decided not to implement a column generation approach.
1.4 Formulation of the Nodes Model for tankers scheduling

We now describe the exact MIP model that we formulated at the beginning for trying to solve the problem.

1.4.1 Sets definition

- \( B \) = Set of available tankers: BT Antofagasta, BT Arica, Abtao, BT Lama and PGA
- \( I_L \) = Set of loading ports: Quintero and San Vicente
- \( I_D \) = Set of unloading ports of the network (demand points): Arica (ARI), Iquique (IQQ), Mejillones (MEJ), Antofagasta (ANT), Barquito (BAR), Caldera (CAL), Guayacan (GUA), Pureo (PUR), Chacabuco (CHA) and Magallanes (MAG)
- \( I = I_L \cup I_D \)
- \( K \) = Saleable products: 93 octane gasoline (G93), 97 octane gasoline (G97), diesel (DIE), jet fuel (JET) and fuel oil (FO)
- \( V \) = Potential trips for the tankers, namely, \( v_1, v_2, \ldots \)
- \( U(i) \) = Define the number of agreed visits to each port \( i \) during the planning horizon. For instance, \( U(CAL) = \{ u_1, u_2, u_3 \} \), that is, Caldera requires 3 visits
- \( E(b) \) = Set of potential stowage configurations of tanker \( b \), namely, \( e_1, e_2, \ldots \)
- \( D \) = Define the days of the planning horizon, typically one or two months
- \( N \) = Define the set of allowed arcs in the network (excluding loops \( (i, i) \))

1.4.2 Parameters

We will now introduce the main parameters used in the model.

- \( \text{dem}_{i,k} \) = Monthly demand of product \( k \) at port \( i \) (\( m^3 \))
- \( c_i \) = Number of required visits at port \( i \) during the time planning horizon. Note that \( \text{dem}_{i,k} / c_i \) represents the ideal unloaded volume per visit if the port is being supply in an homogeneous scheme
- \( \text{DevPen}_{i,k} \) = Artificial penalty for deviating from the ideal unloaded volume of product \( k \) at port \( i \) (US$)
- \( \text{cap}_{b,e} \) = Capacity for product \( k \) in tanker \( b \) while using stowage configuration \( e \) (\( m^3 \))
- \( AA_{i,u} \) = 1, if port \( i \) must be visited by \( u \)-th time during the planning horizon; 0, otherwise
- \( t_{i,j}^b \) = Average traveling time of tanker \( b \) going from port \( i \) to \( j \) (hr)
- \( O_{i,u} \) = Starting time for time window \( u \) at port \( i \) (hr)
- \( F_{i,u} \) = Finishing time for time window \( u \) at port \( i \) (hr)
• \(l_{r_{b,k}}\) = Loading rate of product \(k\) into tanker \(b\) (\(m^3/\text{hr}\))
• \(u_{r_{b,k}}\) = Unloading rate of product \(k\) from tanker \(b\) (\(m^3/\text{hr}\))
• \(AT_b\) = Time at which tanker \(b\) becomes available at the loading port for its first trip of the planning horizon (hr)
• \(MCost_{b,i}\) = Mooring cost of tanker \(b\) at port \(i\) (US$)
• \(TCost_{b,i,j}\) = Transportation cost of tanker \(b\) for going from port \(i\) to port \(j\) (US$)
• \(LCost_b\) = Unit loading cost of tanker \(b\) at the loading port (US$/m^3)
• \(UCost_{b,i}\) = Unit unloading cost of tanker \(b\) at port \(i\) (US$/m^3)
• \(M_1, \ldots, M_9\) = Large enough constants used in some constraints for logical purposes

### 1.4.3 Decision Variables

We now introduce the decision variables that will decide on the best trips for each tanker.

\[
Y_{b,v} = \begin{cases} 
1 & \text{if tanker } b \text{ makes trip } v \\
0 & \text{otherwise}
\end{cases}
\]

\[
X_{b,v}^{i,j} = \begin{cases} 
1 & \text{if tanker } b \text{ on trip } v \text{ goes from } i \text{ to } j \\
0 & \text{otherwise}
\end{cases}
\]

\[
Q_{b,v}^{u,i} = \begin{cases} 
1 & \text{if the } u\text{-th visit to port } i \text{ is made by tanker } b \text{ on trip } v \\
0 & \text{otherwise}
\end{cases}
\]

\[
Z_{b,v}^{e} = \begin{cases} 
1 & \text{if tanker } b \text{ on trip } v \text{ chooses stowing configuration } e \\
0 & \text{otherwise}
\end{cases}
\]

• \(VO_{b,v}^k\) = Volume of product \(k\) loaded on tanker \(b\) for trip \(v\) (\(m^3\))
• \(VD_{b,v}^k\) = Volume of product \(k\) to be delivered at port \(i\) by tanker \(b\) on trip \(v\) (\(m^3\))
• \(\alpha_{i,k}\) = Percentile deviation from the ideal unloaded volume of product \(k\) at port \(i\)
• \(W_{b,v}^{i,u}\) = Time of arrival of tanker \(b\) on trip \(v\) at port \(i\) for the \(u\)-th visit (hr)
• \(ST_{b,v}\) = Starting time of trip \(v\) of tanker \(b\) (hr)
• \(LC\) = Loading cost for the fleet during the planning horizon (US$)
• \(TC\) = Traveling cost for the fleet during the planning horizon (US$)
• \(MC\) = Mooring cost for the fleet during the planning horizon (US$)
• \(UC\) = Unloading cost for the fleet during the planning horizon (US$)
• \(DC\) = Penalty cost for deviating from the ideal unloads for the fleet during the time horizon (US$)
• \(OC\) = Overall operational cost for the fleet during the planning horizon (US$)
1.4.4 Constraints

1. If tanker \( b \) makes trip \( v \) it must leave the loading port and go to a demand one as first stop

\[
\sum_{i \in I_D} X_{b,v}^{0,i} = Y_{b,v}, \quad \forall b, v, 0 \in I_L
\]  

(1.1)

2. If tanker \( b \) makes trip \( v \) it must return to the loading port from a demand one

\[
\sum_{i \in I_D} X_{b,v}^{i,0} = Y_{b,v}, \quad \forall b, v, 0 \in I_L
\]  

(1.2)

3. If tanker \( b \) makes trip \( v \) it must pick a stowing configuration among its set of available ones

\[
\sum_{e \in E(b)} Z_{b,v}^{e} = Y_{b,v}, \quad \forall b, v
\]  

(1.3)

4. If tanker \( b \) on trip \( v \) visits port \( j \) it must go from \( j \) to a another port

\[
\sum_{i \in I} X_{b,v}^{i,j} = \sum_{i' \in I} X_{b,v}^{i',j'}, \quad \forall b, v, j \in I_D
\]  

(1.4)

5. If tanker \( b \) does not make trip \( v \), there is not starting time for it

\[
ST_{b,v} \leq M_1 \cdot Y_{b,v}, \quad \forall b, v
\]  

(1.5)

6. Tanker \( b \) can not make trip \((v+1)\) if it did not make trip \( v \)

\[
Y_{b,v+1} \leq Y_{b,v}, \quad \forall b, v
\]  

(1.6)

7. If tanker \( b \) is going to make its first trip the starting time for that trip has to be later that its availability time on loading port plus the loading time for that first trip

\[
ST_{b,v1} \geq AT_b + \sum_k V_{b,v1}^{k} - M_2 (1 - y_{b,v1}) \quad , \quad \forall b
\]  

(1.7)

8. If tanker \( b \) is going to make its trip \((v+1)\), the starting time for that trip must be later than the time of arrival to the last demand point \( i \) in trip \( v \) plus the unloading time in \( i \) plus the transportation time from \( i \) to the loading port and plus the loading time for trip \((v+1)\)

\[
ST_{b,v+1} \geq W_{b,v}^{i,u} + \sum_k V_{b,v}^{k} + t_{i,0} + \sum_k V_{b,v+1}^{k} + \\
- M_3 (3 - y_{b,v+1} - Q_{b,v}^{u,i} - X_{b,v}^{i,0}) \quad , \quad \forall b, v, i \in I_D, u \in U(i)
\]  

(1.8)

9. The \( u \)-th visit to port \( i \) must be assigned to some tanker in some trip

\[
\sum_b \sum_v Q_{b,v}^{u,i} = AA_{i,u}, \quad \forall i \in I_D, \forall u \in U(i)
\]  

(1.9)
10. If tanker \( b \) visits port \( j \) on its trip \( v \), this visit will count as just one the visits to that port
\[
\sum_{u \in U(j)} Q_{b,v}^u = \sum_{i:(i,j) \in N} X_{b,v}^{i,j} , \quad \forall j \in I_D, \forall b, v
\]  
\[(1.10)\]

11. Each port \( j \) should be visited \( c_j \) times during the time horizon
\[
\sum_{b} \sum_{v} \sum_{i:(i,j) \in N} X_{b,v}^{i,j} = c_j , \quad \forall j \in I_D
\]  
\[(1.11)\]

12. Tanker \( b \) on trip \( v \) can unload a positive volume on demand port \( j \) just if it visits \( j \) in that trip
\[
VD_{b,v}^{i,j} \leq M_4 \sum_{i:(i,j) \in N} X_{b,v}^{i,j} , \quad \forall j \in I_D, \forall b, v
\]  
\[(1.12)\]

13. The unloaded volume of product \( k \) at port \( j \) by tanker \( b \) on trip \( v \) can not exceed the upper bound allowed
\[
VD_{b,v}^{i,k} \leq \frac{\text{dem}_{i,k}}{c_j}(1 + \alpha_{j,k}) + M_5(1 - \sum_{i:(i,j) \in N} X_{b,v}^{i,j}) , \quad \forall b,k,v,j \in I_D
\]  
\[(1.13)\]

14. The unloaded volume of product \( k \) at port \( j \) by tanker \( b \) on trip \( v \) can not be less than the lower bound allowed
\[
\frac{\text{dem}_{i,k}}{c_j}(1 - \alpha_{j,k}) - M_5(1 - \sum_{i:(i,j) \in N} X_{b,v}^{i,j}) \leq VD_{b,v}^{i,k} , \quad \forall b,k,v,j \in I_D
\]  
\[(1.14)\]

15. The demand of product \( k \) at each port \( i \) must be satisfied
\[
\sum_{b} \sum_{v} VD_{b,v}^{i,k} = \text{dem}_{i,k} , \quad \forall i \in I_D, \forall k
\]  
\[(1.15)\]

16. The total unloaded volume of product \( k \) by tanker \( b \) on trip \( v \) can not exceed the capacity of product \( k \) allowed in the stowing configuration that was selected for that trip
\[
\sum_{i \in I_D} VD_{b,v}^{i,k} \leq \sum_{e \in E(b)} Z_{b,e}^e \cdot \text{cap}_{b,k}^e , \quad \forall b,v,k
\]  
\[(1.16)\]

17. Tanker \( b \) on trip \( v \) must unload the total volume of product \( k \) that was loaded with
\[
VO_{b,v}^k = \sum_{i \in I_D} VD_{b,v}^{i,k} , \quad \forall b,v,k
\]  
\[(1.17)\]

18. If the \( u \)-th visit to port \( i \) is not made by tanker \( b \) on trip \( v \), then there is not time associated
\[
W_{b,v}^{i,u} \leq M_6 \cdot Q_{b,v}^{u,i} , \quad \forall b,v,i \in I_D, u \in U(i)
\]  
\[(1.18)\]

19. The arrival time to the first port \( i \) of tanker \( b \) on trip \( v \) must be later that the starting time of that trip at the loading port plus the transportation time to \( i \)
\[
W_{b,v}^{i,u} \geq ST_{b,v} + t_{0,i} - M_T(1 - X_{b,v}^{0,i}) , \quad \forall b,v,i \in I_D, u \in U(i)
\]  
\[(1.19)\]
20. The arrival time to port \( j \) of tanker \( b \) on trip \( v \) must be later than the arrival time to port \( i \) plus the unloading time in \( i \) and traveling time from \( i \) to \( j \)

\[
W^{j,u}_{b,v} \geq W^{i,u'}_{b,v} + \sum_{k} \frac{V D_{b,v}^{i,k}}{t_{i,j,k}^{b}} + t_{i,j}^{b} - M_{9}(1-X^{i,j}_{b,v}) , \quad \forall b, v, (i, j) \in N, i \in I_D, u \in U(j), u' \in U(i) 
\]

(1.20)

21. The arrival time for visit \( u \) at port \( i \) should satisfy the time window designated to it

\[
O_{i,u} - M_{9}(1-Q^{u,i}_{b,v}) \leq W^{i,u}_{b,v} \leq F_{i,u} + M_{9}(1-Q^{u,i}_{b,v}) , \quad \forall b, v, i \in I_D, u \in U(i) 
\]

(1.21)

22. Total loading operation cost for the fleet during the time horizon

\[
LC = \sum_{b} \sum_{v} \sum_{k} VO^{k}_{b,v} \cdot LC_{b,v} 
\]

(1.22)

23. Total traveling cost for the fleet during the time horizon

\[
TC = \sum_{b} \sum_{v} \sum_{(i,j) \in N} X^{i,j}_{b,v} \cdot TC_{b,i,j} 
\]

(1.23)

24. Total mooring cost for the fleet during the time horizon

\[
MC = \sum_{b} \sum_{v} \sum_{i} \sum_{u} Q^{u,i}_{b,v} \cdot MC_{b,i} 
\]

(1.24)

25. Total unloading operation cost for the fleet during the time horizon

\[
UC = \sum_{b} \sum_{v} \sum_{i} \sum_{u} V D^{i,k}_{b,v} \cdot UC_{b,i} 
\]

(1.25)

26. Total cost for deviating from the ideal unloads on ports for the fleet during the time horizon

\[
DC = \sum_{i} \sum_{k} \alpha_{i,k} \cdot DevPen_{i,k} 
\]

(1.26)

27. Finally, we define the nature of the decision variables

\[
X^{i,j}_{b,v}, Y_{b,v}, Q^{u,i}_{b,v} \in \{0, 1\}, \forall b, v, i, j, u \\
VO^{k}_{b,v}, V D^{i,k}_{b,v}, W^{i,u}_{b,v}, ST_{b,v}, LC, TC, MC, UC, DC, OC \geq 0, \forall b, v, i, k, u 
\]

1.4.5 Objective function structure

We are minimizing \( OC \), the overall operational cost for the fleet during the time horizon:

\[
OC = LC + TC + MC + UC + DC 
\]
1.5 Main features of the Route Model for tankers scheduling

As was mentioned before this model is based on complete routes. For each trip, the route is a sequence of ports starting from and returning to the same loading port. This model is similar to the Node Model but with a limited subset $R$ of all routes possible, built after consultation with the Head of Logistics and schedulers. They looked in particular at the main operational aspects and characteristics of the tankers and the ports.

We replaced the arc decision variables $X_{b,v}^{i,j}$ by the aggregate route decision variables

$$XX_{b,v}^{r} = \begin{cases} 1 & \text{if tanker } b \text{ on trip } v \text{ uses route } r \\ 0 & \text{otherwise} \end{cases}$$

The size of the model is considerably reduced. For instance, a node model with 62,000 binary variables turned into a routes model with less than 8,000 binary variables.

New parameters need to be defined, for instance, $n_{r,j}$ is a binary parameter equal to 1 if and only if port $j$ is on route $r$. Some constraints need to be rewritten, for instance, constraint number (11) becomes

$$\sum_{b} \sum_{v} \sum_{r \in R: n_{r,j} = 1} XX_{b,v}^{r} = c_{j}, \quad \forall j \in I_{D} \quad (1.27)$$

The objective function changes as well. For instance, constraint number (22) becomes

$$TC = \sum_{b} \sum_{v} \sum_{r \in R} XX_{b,v}^{r} \cdot TCost_{r}, \quad (1.28)$$

where $TCost_{r}$ corresponds to the sum of all the traveling costs of the arcs on route $r$

1.6 Interaction of the two models

We could not solve the Node Model from scratch because of its size. Instead we worked first on building a meaningful set $R$ of routes and then a model based on these routes. The optimal solution of this Route Model can then be used as a hot start for the Nodes Model.

The sequence of steps that we are currently following is:

1. Select a meaningful set $R$ of routes, large enough to contain a fair number of feasible routing options, and not too large, so that it can be solved easily

2. Solve the corresponding Route Model
3. Extract the routes $r^*$ that are part of the optimal solution found in (2), that is, the routes $r^*$ with $XX^*_{b,v} = 1$

4. Solve the Node Model over the variables $X_{b,v}^{ij}$ for all arcs $(i,j)$ in the network starting from the feasible solution provided by (3), that is, $X_{b,v}^{ij} = 1, \forall (i,j) \in r^*$

The optimal solution found for the Node Model is the one provided to the scheduler and it is then implemented, possibly with some minor adjustments due to last minute changes in the parameters

### 1.7 Implementation of the model at ENAP

The mathematical models described in the previous section were coded in GAMS 24.4.6 using CPLEX 16.2 as a solver. In terms of the options in GAMS-CPLEX for the prioritization in the branch and bound algorithm, a balance between feasibility and optimality was chosen. The Windows machine used to run the code was a Dell XPS Core i7 with 8GB RAM, a 2.4 GHz processor and a solid state drive.

For illustrative purposes, in this section we first describe the data for the month of June 2016. These data were used to run the two-model approach described in the previous section. The monthly demand for the five products was about 250,000 $m^3$.

In addition, the model has been successfully used for evaluating the renewal or cancellation of the renting contract for some tankers of the fleet.

#### 1.7.1 Parameters used in the June 2016 run

**Monthly demand of product $k$ at port $i$** ($dem_{i,k}$)

In table 2.1 the monthly demand ($m^3$) of product $k$ at port $i$ is detailed. As can be seen, there are ports with no demand for some products.

<table>
<thead>
<tr>
<th>Port</th>
<th>G93</th>
<th>G97</th>
<th>JET</th>
<th>DIE</th>
<th>FO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARI</td>
<td>4,835</td>
<td>2,860</td>
<td>8,778</td>
<td>1,540</td>
<td></td>
</tr>
<tr>
<td>IQQ</td>
<td>8,291</td>
<td>5,652</td>
<td>5,324</td>
<td>4,747</td>
<td>7,667</td>
</tr>
<tr>
<td>MEJ</td>
<td></td>
<td>4,719</td>
<td>1,947</td>
<td>8,041</td>
<td></td>
</tr>
<tr>
<td>ANT</td>
<td>8,967</td>
<td>6,073</td>
<td>4,763</td>
<td>28,941</td>
<td></td>
</tr>
<tr>
<td>BAR</td>
<td></td>
<td>440</td>
<td>3,510</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAL</td>
<td>2,851</td>
<td>1,746</td>
<td>836</td>
<td>14,522</td>
<td></td>
</tr>
<tr>
<td>GUA</td>
<td>11,340</td>
<td>5,971</td>
<td>1,089</td>
<td>24,166</td>
<td></td>
</tr>
<tr>
<td>PUR</td>
<td>11,766</td>
<td>6,787</td>
<td>2,865</td>
<td>32,836</td>
<td></td>
</tr>
<tr>
<td>CHA</td>
<td>1,288</td>
<td>588</td>
<td>8,916</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAG</td>
<td>3,000</td>
<td>13,000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 1.1: Monthly demand for June 2016*
Stowing configurations for the tankers

In Figure 1.4 we present a set of possible aggregate stowing configurations for specific tankers as indicated by the schedulers considering demands and physical constraints. Each aggregate configuration corresponds to a feasible stowage configuration as seen in Figure 1.3. For instance, tanker Abtao has a capacity of 51,734 $m^3$ and in $e_3$ the aggregate capacity allocated for G93 is 12,700, the capacity for G97 is 3,700, for Jet fuel is 8,046, for Die is 18,192 and, finally, for FO is 9,096.

<table>
<thead>
<tr>
<th>Tanker</th>
<th>SC</th>
<th>G93</th>
<th>G97</th>
<th>JET</th>
<th>Die</th>
<th>FO</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT Antofagasta</td>
<td>e1</td>
<td>9271</td>
<td>8325</td>
<td>6265</td>
<td>28436</td>
<td>0</td>
<td>52297</td>
</tr>
<tr>
<td></td>
<td>e2</td>
<td>14080</td>
<td>10899</td>
<td>4157</td>
<td>23161</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e3</td>
<td>13439</td>
<td>4157</td>
<td>6265</td>
<td>28436</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>BT Arica</td>
<td>e1</td>
<td>9268</td>
<td>8324</td>
<td>6264</td>
<td>18914</td>
<td>9446</td>
<td>52216</td>
</tr>
<tr>
<td></td>
<td>e2</td>
<td>9268</td>
<td>6264</td>
<td>8324</td>
<td>18914</td>
<td>9446</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e3</td>
<td>9268</td>
<td>6264</td>
<td>0</td>
<td>27238</td>
<td>9446</td>
<td></td>
</tr>
<tr>
<td>Abtao</td>
<td>e1</td>
<td>9000</td>
<td>7400</td>
<td>8046</td>
<td>18192</td>
<td>9096</td>
<td>51734</td>
</tr>
<tr>
<td></td>
<td>e2</td>
<td>9000</td>
<td>7400</td>
<td>4023</td>
<td>22215</td>
<td>9096</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e3</td>
<td>12700</td>
<td>3700</td>
<td>8046</td>
<td>18192</td>
<td>9096</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e4</td>
<td>12551</td>
<td>4505</td>
<td>4548</td>
<td>21052</td>
<td>9096</td>
<td></td>
</tr>
<tr>
<td>BT Lama</td>
<td>e1</td>
<td>4150</td>
<td>3250</td>
<td>0</td>
<td>7200</td>
<td>0</td>
<td>14600</td>
</tr>
<tr>
<td></td>
<td>e2</td>
<td>3050</td>
<td>1250</td>
<td>0</td>
<td>10300</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e3</td>
<td>3050</td>
<td>1250</td>
<td>750</td>
<td>9550</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e4</td>
<td>3250</td>
<td>1700</td>
<td>750</td>
<td>8900</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>PGA</td>
<td>e1</td>
<td>11311</td>
<td>6261</td>
<td>5000</td>
<td>35000</td>
<td>0</td>
<td>57572</td>
</tr>
<tr>
<td></td>
<td>e2</td>
<td>11311</td>
<td>6261</td>
<td>10000</td>
<td>30000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e3</td>
<td>11316</td>
<td>6256</td>
<td>0</td>
<td>40000</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1.4: Aggregated configurations considered for the June 2016 run

1.7.2 Description of the optimal solution for the June 2016 run

The following tables display different complementary aspects of the optimal solution to the June 2016 run. They show information from the points of view of:

1. The tankers including routes and dates of the stops
2. The ports including delivery times windows and volumes delivered
3. The schedulers showing tanker trips with dates, volumes and ports visited

Table 1.2 shows for each visit at each port the tanker ID, its trip, its route and the day of the visit. For instance, the port of Caldera is visited for the second time in June 2016, on day 16 by tanker BT Arica, which is on its second trip, taking route 102.
Table 1.2: Tanker schedules and routes in the optimal solution

Table 1.3 shows for each tanker and each of its trips the route selected and its description. For instance, tanker Abtao on its second trip is taking route 409 which starts at the loading port of Quintero, then visits Guayacan, then Caldera, then Mejillones, then Arica and, finally, comes back to Quintero

Table 1.4 shows for each port and each visit the time window and the day of the visit. For instance, the first time window for Guayacan was between day 2 and 4, that is [2, 4] and the model suggested to arrive of day 4. The second time window was [12, 14] and the model picked day 12. The third and final window was [22, 24] and the model picked day 24.
Table 1.4: Time windows \([O_{i,u}, F_{i,u}]\) for the visits at each port and the actual day suggested in the optimal solution

<table>
<thead>
<tr>
<th>Port</th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(O_{i,u1})</td>
<td>(F_{i,u1})</td>
<td>(O_{i,u2})</td>
</tr>
<tr>
<td>ARI</td>
<td>13</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td>IQQ</td>
<td>11</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>MEJ</td>
<td>9</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td>ANT</td>
<td>3</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>BAR</td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>CAL</td>
<td>4</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>GUA</td>
<td>2</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>PUR</td>
<td>6</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>CHA</td>
<td>3</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>MAG</td>
<td>18</td>
<td>18</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 1.5 shows for each port and each product delivered the monthly demand and the amount delivered per visit. For instance, the port of Antofagasta, which requires three visits per month, has a monthly demand of Diesel of 28,941. In the first visit, the amount delivered is 10,901, in the second visit is 8,393 and, finally, in the third visit is 9,647. In this particular case, the ideal unloaded amount per visit in order to have an 100% homogeneous delivery process would have been 9,647. Based on that, we noticed that the deviation in visits 1 and 2 is below 13% and is 0% for the third visit.
<table>
<thead>
<tr>
<th>Port</th>
<th>Product</th>
<th>DEM</th>
<th>Vol visit 1</th>
<th>Vol visit 2</th>
<th>Vol visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARI</td>
<td>CQI</td>
<td>4.635</td>
<td>2.065</td>
<td>2.535</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CDI</td>
<td>2.861</td>
<td>1.010</td>
<td>1.244</td>
<td></td>
</tr>
<tr>
<td></td>
<td>JET</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DIE</td>
<td>8.778</td>
<td>3.018</td>
<td>4.060</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FO</td>
<td>1.540</td>
<td>0.668</td>
<td>0.810</td>
<td></td>
</tr>
<tr>
<td>IQQ</td>
<td>CQI</td>
<td>8.071</td>
<td>2.669</td>
<td>4.684</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CDI</td>
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<td>2.459</td>
<td>3.193</td>
<td></td>
</tr>
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<td></td>
<td>JET</td>
<td>5.324</td>
<td>2.316</td>
<td>3.008</td>
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</tr>
<tr>
<td></td>
<td>DIE</td>
<td>4.747</td>
<td>2.066</td>
<td>2.687</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FO</td>
<td>7.697</td>
<td>3.082</td>
<td>3.992</td>
<td></td>
</tr>
<tr>
<td>MEJ</td>
<td>CQI</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CDI</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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Table 1.5: Volume delivered at each port in the optimal solution

Table 1.6 summarizes all the previous information for the schedulers. It contains the following:

- For each tanker, its trip is represented by a different shade of the same color (e.g., dark orange then light orange). The tanker BT Antofagasta is represented in blue, the tanker BT Arica in green, the tanker Abtao in orange, the tanker Lama in red and, finally, the tanker PGA in yellow.

- For each demand port, each product and each visit, the amount delivered, if any, is shown in the corresponding cell. Loading ports are not displayed in the table.
1.8 Implementation of the graphical user interface (GUI) and Impact

In the process of developing the two optimization models, we had a frequent interaction with the maritime schedulers at ENAP. Based on this we understood what information and reports would be useful to them. The GUI that we built is user friendly and allows the scheduler to enter the main parameters of the model before the runs.

The user enters the parameters on the GUI and presses a link to GAMS. As a consequence an Excel macro runs GAMS-CPLEX in the background and displays the results of the optimal schedule for the entire fleet during the time horizon. The results are presented in different views that were developed during frequent meetings with the users taking into considerations their preferences. Nowadays we have meetings on a monthly basis in order to check the status of the system, run particular scenarios or other requirements.

In terms of the impact of the model a common KPI (key performance indicator) used in the oil and gas industry is the unit operational cost, measured in US$/m^3$. In particular, in the case of maritime distribution of refined petroleum products by tanker, the KPI is Total operational cost divided by the Total volume transported.

In the case of ENAP, on average, the unit cost before the utilization of the model was

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<th>Class</th>
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<th>Unit Cost</th>
<th>Volume</th>
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Table 1.6: Detailed schedule for the fleet in the optimal solution

19
15 US$/m³. After starting using the model systematically the unit cost went down to 13.7 US$/m³, that is, a reduction of approximately 9%.

1.9 Conclusion

In this paper we showed an innovative approach to solve a complex large scale MIP model for optimizing the tankers scheduling at ENAP, the state-owned petroleum company in Chile. The original exact model was unsolvable on GAMS-CPLEX, so our approach was based on reducing dramatically the number of feasible routes by taking into consideration many operational aspects. As a result we built a more compact and tractable model, which we solve to optimality and get the optimal solution as a hot start to the original model.

This strategy is novel in the field of maritime transportation of petroleum products and was implemented with a graphic user interface that runs the optimization model. This tool has been a great help for ENAP schedulers and is saving up to 9% of the operational cost for the maritime distribution system at the company.

We believe that this kind of approach can be used to tackle other complex scheduling problems in other industries.

In addition, we see an interesting potential in linking this tool with other simulation or optimization models that are being used in the company. For instance, we built a model for optimizing the distribution of products by pipelines. Therefore, a model that integrates the maritime and pipeline distribution system could be an extension of this applied research.
Chapter 2

Optimizing the ENAP’s Pipeline Scheduling System

2.1 Introduction

ENAP (Empresa Nacional del Petroleo) is the state-owned petroleum company in Chile. The firm does oil and gas exploration and production in Chile and other countries. Its main business is transforming crude oil into refined petroleum products to be distributed and sold to large retail companies of the Chilean industry. One of the distribution systems that the ENAP uses is a network of pipelines. In this work we describe an approach developed for the company to rationalize the distribution of some oil products through one of its three pipelines. This 360 km pipeline connects their BioBio refinery to three demand sites further north, in Chillan (a client site), Linares and San Fernando (ENAP’s sites). Inventory levels in the refinery tanks increase following production at the refinery and import of gasoline and diesel, and decrease by the amounts of refined oil products sent on the pipeline. Ideally, one wants to deliver on time to the demand sites the required quantities and to control the amount of polluted mixes than can occur depending on the sequence of products selected to send through the pipeline. Optimizing these operations can be modelled via linear mixed-integer programming. When constructing the model, one needs to keep track over time of the sequence and amounts of products in the pipeline, as well as of the tank levels at the refinery and at the demand sites. Tank capacities and depletion rates affect the amounts that can be delivered over time.

At the demand sites, there is demand for six different products, which we will call 'saleable products': diesel, propane, butane, two different grades of gasoline, and domestic kerosene. These are injected into the pipeline at the refinery and one must decide, at each change of product, how much of which product to send next. Two consecutive products of the same type but of different grades will create in their contact area a mixed product that can be sold at the cheaper price. Some specific products cannot immediately follow each other, and if need be will be separated by a certain
amount of kerosene. The mixed products created by the kerosene, generically called interface, need to be reprocessed at a cost. The objective is to schedule the injection of the products into the pipeline and determine the amounts of products in order to minimize the sum of operating costs, reprocessing costs and the artificial penalties for stocks falling below the established safety stocks. An equilibrium must be reached between minimizing the amount of mixed kerosene to be reprocessed by sending long batches of single products, and avoiding penalties for letting demand point inventories get depleted by sending short batches of single products.

ENAP had been using a manual approach for scheduling, based on experience and intuition. The model developed allowed to improve the decision making process reducing both reprocessing of products and penalties.

The company has been using the model very successfully, realizing savings of about 10% compared to previous years. The program is written in GAMS. The use of the system has been facilitated by a user friendly GUI that is used on a regular basis. The GUI allows the operator to adjust some parameters in EXCEL, and to run the GAMS code with just a click.

There is a small body of papers describing research on pipeline scheduling. Relvas formulated an MILP model based on a convex-hull formulation ([4]) that includes constraints such as mass balances, distribution constraints and product demands. Results generated include the inventory levels at all locations, the distribution of products between the depots and the ordering of products in the pipeline. This approach is capable to build a schedule for a very short time horizon. A more refined model including inventory constraints is presented by Pinto in [2]. Key decisions in this model involve loading and unloading tanks and pipeline operations. This model includes operational constraints, such as mass balances, product demands, sequencing constraints and logical constraints. Results generated include the distribution of products among the depots and the ordering of products in the pipeline. Two examples are solved, including a real-world system composed of five depots and distributing gasoline, diesel, liquefied petroleum gas and jet fuel for a 3-day time horizon.

The main contributions of our work are:

- We have developed a system based on a MIP model and a friendly user interface that is being successfully used by ENAP for scheduling the distribution of petroleum products through the pipeline for a whole month.

- The system developed deals with the trade-off between having fewer batch interfaces and on the other hand satisfy client’s demand.

- The way we constructed a set of feasible sequences for a multiproduct pipeline is novel and presents an innovative approach for reducing the dimensionality of the problem. It can be seen that for the 6 requested products, a 10 batch sequence gives $6^{10}$, that is, more than 60 million combinations for allocating the different products.
2.2 The pipelines system at ENAP and problem description

ENAP uses a 360 kms pipeline which starts at ENAP BioBio Refinery (ERBB) and goes north having 3 demand points, from south to north, Chillán (Chi), Linares (Lin) and San Fernando (SF) as shown in figure 2.1. This last point corresponds to the end of the pipeline in its regular configuration. The pipeline transports 6 products and at each demand point there are individual tanks to store them.

![Figure 2.1: Pipeline network](image)

In commercial terms, the company has annual contracts with its clients, in which demands are given in monthly volumes, allowing some tolerance. Both players have rights and obligations. The main factors that drive the distribution policies are that the volume should be delivered on time, on specification terms, and in the right amounts. In the case of Chillán, the monthly demands are known but only estimated information about storage capacity, initial inventories and safety stocks is available. Indeed a client runs that facility and ENAP is not responsible for managing its inventory. In this location ENAP is only responsible for delivering the monthly demands as homogeneously as possible according to the monthly agreements. Given the demand points in this pipeline network, on average, ENAP’s monthly demand is approximately 150,000 m3.

In the case of Linares and San Fernando ENAP owns the terminals, from where the demands of downstream clients must be satisfied.

Based on the terminology used in the petroleum industry, we will call a batch to a volume amount of a single product being injected in the pipeline. Each batch injected at the origin should be determined taking into account its arrival time at the demand points and the volume each client is going to take from it. There are 6 products to be injected in the pipeline in batches and there are volume limitations for them because of operational issues. For instance, it does not make sense to inject a small batch of 10 m3, so at least 100 m3 are required per batch.

The planning horizon is a full month in which the demand for each particular product at each destination should be fulfilled by the sum of the volumes of all the amounts of that product delivered to that client. Ten days before the start of a month, the clients reveal their demand per product for the incoming month and ENAP must build
a schedule for the delivery of each product to each client at each point. In addition, products must satisfy volume and flow rate constraints in the pipeline.

One feature that makes this problem very particular, in contrast with petroleum transportation by vessels, is the fact that the consecutive batches of different products are NOT separated by any physical method. That is, the tail of the batch ahead is in direct contact with the head of the batch behind it. This creates a mix volume that is neither of the adjacent products and must be reprocessed at the refinery unless it can be solved (e.g., G97 mix with G93 can be sold as G93). In addition, in some cases the insertion of a batch of kerosene (Ker) is needed to avoid direct contact between two products. This volume needs reprocessing as well. The contaminated product and the Ker must be recollected for reprocessing at a cost, and the whole amount is called slop.

ENAP’s schedulers used to do this assignment by hand and just based on their experience and common sense. It is clear that given the combinatorial nature of this problem, this manual procedure was suboptimal and ENAP’s cost was higher than necessary. Actually, the schedulers used to repeat some patterns of batches that seemed to work reasonably well and satisfied the chemical constraints. The approach however did not take full advantage of the sequences and there were often difficulties delivering on time according to the agreed upon schedule. Delays resulted in significant penalty cost for ENAP.

Motivated by this situation, we developed a mathematical model that captures the logical decisions involved and finds a schedule that minimizes the monthly costs. The model decides which type of sequences to use, in which order and the volume of product in each batch to minimize the operating cost, i.e., the sum of penalty and reprocessing costs.
2.3 General methodology for addressing the problem

From a practical point of view we can formulate the problem described above as follows. Given a monthly demand for six refined oil products at three demand points along the pipeline, the scheduler should decide the order, volume and timing of the batches entering the pipeline while satisfying a set of operational constraints and so as to minimize the overall operating cost. Considering the fact that the refinery supplies volumes to different systems, namely the San Vicente Port for cabotage vessels, the truck loading facility and the pipeline, we include in our model not just the inventory levels at the demand points but also the inventory of each product available at the refinery. As Figure 2.2 shows, the inventory for each product increases through production at the refinery and direct imports already refined products, and decreases as products are sent via cabotage vessels, trucks and the pipeline. Here, we are only concerned with distribution through the pipeline, and consider the volumes available as given inputs.

Figure 2.2: Inventory dynamics of a tank at the refinery: The level goes up through imports and refinery production, the level goes down through loading of cabotage vessels, trucks and the pipeline

For decades ENAP pipeline schedulers used to do the scheduling just based on their long experience and chemical background. They know for any pair of product whether they can be in contact or whether contact should avoided. After several technical meetings with people from the refinery and with operators, we defined four main types of sequences that are feasible to inject into the pipeline ($S_1, S_2, S_3, S_4$). A sequence consists of several batches following each other on specific order.

Figure 2.3: Describes the 4 types of sequences considered. Each sequence is characterized by its positions $p_1, p_2, ..., p_6$. Sequences $S_1-S_3$ have 6 positions and sequence $S_2-S_4$ have 4 positions
As an example, in sequence type $S_1$ the first position is for diesel ($Die$), the second is for kerosene ($Ker$), the third is for 93 octanes gasoline ($G_{93}$), the fourth is for 97 octanes gasoline ($G_{97}$), the fifth is for 93 octanes gasoline ($G_{93}$) and the sixth one is for kerosene ($Ker$).(see figure 2.3). A crucial decision that the model makes is the order in which the sequences are entering into the pipeline and the volumes in each batch of all sequences. For instance, if the first sequence entering the pipeline is type $S_1$, the second is type $S_2$ and the third is type $S_4$, we would see the following:

![Diagram of sequences]

*Figure 2.4: Example of sequences. A sequence $S_1$ is the first entering the pipeline, $S_2$ is the second and $S_4$ the third*

The role of the batches called $Ker$ (not a saleable commodity) is to isolate certain pairs of products by avoiding direct contact between them. One the goals of the model is to minimize the monthly volume of $Ker$ injected in the pipeline because it has a reprocessing cost. If the final saleable batch of a sequence is the same as the initial batch of the incoming sequence, then no $Ker$ is needed as a separator.

In order to explain graphically how a batch of product reaching a demand point is split between the amount supplied to a client and the amount remaining in the pipeline, considered the following example. There is a batch of 3,000 $m^3$ of $G_{93}$ to be allocated 800 $m^3$ for Chillan, 1,000 $m^3$ for Linares and 1,200 $m^3$ for San Fernando. In addition, a batch of 2,000 $m^3$ of $G_{93}$ to be allocated 1,000 $m^3$ for Chillan, 500 $m^3$ for Linares and 500 $m^3$ for San Fernando (see figure 2.5).

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Figure 2.5: Splitting a batch. From a batch of 3,000 m$^3$ of G93 (red), 800 m$^3$ are delivered in Chillan, 1,000 m$^3$ in Linares and 1,200 m$^3$ in San Fernando. In parallel, from a batch of 2,000 m$^3$ of G93 (blue), 1,000 m$^3$ are delivered in Chillan, 500 m$^3$ in Linares and 500 m$^3$ in San Fernando.
2.4 The pipeline scheduling optimization model at ENAP

We now introduce the definitions and notation used in the model formulation.

2.4.1 Set definitions

- $R$ = The refinery in BioBio that supplies the pipeline (Ref)
- $I$ = Demand points in the pipeline network (Chi, Lin and SF)
- $K_s$ = Saleable products: 93 octane gasoline (G93), 97 octane gasoline (G97), diesel (Die), domestic kerosene ($K_{dom}$), propane (C3) and butane (C4)
- $K = K_s \cup \{Ker\}$, where $Ker$ is the kerosene separator
- $S$ = Types of feasible sequences of batches that can be injected at the origin of the pipeline, namely, $S_1, S_2, S_3, S_4$.
- $P$ = Positions of the batches within a sequence, $p_1$ being at the front of the sequence, $p_2$ in second position, and so on. For instance, in $S_4$, product $K_{dom}$ is in second position.
- $L$ = Order of sequences as they enter the pipeline, namely, $l_1, l_2, l_3, \ldots$
- $D$ = Days in the planning horizon (usually 1 to 30)

2.4.2 Parameters

We now introduce the main parameters used in the model.

- $prod_k$ = Production rate of product $k$ at the refinery ($m^3/hr$)
- $tlf_k$ = Volume of product $k$ to be delivered per hour at the truck loading facility near the refinery ($m^3/hr$)
- $dem_{i,k}$ = Monthly demand for product $k$ at point $i$ ($m^3$) ($demh_{i,k}$: hourly demand)
- $Cap_{i,k}$ = Tank storage capacity for product $k$ at point $i$ ($m^3$)
- $Flow_{i,j}$ = Recommended rate of flow between consecutive demand points $i$ and $j$ ($m^3/hr$)
- $SS_{i,k}$ = Safety stock of product $k$ at demand point $i$ ($m^3$)
- $V_{min_{s,p}}, V_{max_{s,p}}$ = Minimum (maximum) volume allowed for the product in position $p$ in sequence $s$ ($m^3$)
- $V_{Smin_{i,s,p}}$ = Minimum volume of the product in position $p$ in sequence $s$ to be supplied at demand point $i$ ($m^3$)
- $Pos_{p,s,k} = 1$, if product $k$ is in position $p$ in sequence $s$; 0, otherwise
- $L_{p,s} = 1$, if $p$ corresponds to the last position in sequence $s$; 0, otherwise
- $m_{s,s'} = 1$, if the last saleable product in sequence $s$ matches (i.e., is the same as) the first saleable product in sequence $s'$; 0, otherwise
- $IntVol_{p,s}$ = Volume of the interface generated in position $p$ of sequence $s$ ($m^3$)
- $DV_{p,s}$ = Degraded/upgraded volume in position $p$ of sequence $s$ ($m^3$). This volume is positive when the volume of the product in position $p$ increases by getting some higher quality product from its neighbors. It is negative when the opposite occurs, there is a loss to a neighbor product, and zero otherwise.
- $VSeg_{i,j}$ = Volume of the pipeline segment between consecutive demand points $i$ and $j$ ($m^3$)
- $Inv_{i,k}$ = Initial inventory level of product $k$ at point $i$ ($m^3$)
- $InvR_0^k$ = Initial inventory level of product $k$ at the refinery ($m^3$)
- $FInvMin_{i,k}, FInvMax_{i,k}$ = Minimum (maximum) level of inventory of product $k$ needed at point $i$ at the end of the planning horizon ($m^3$)
- $VolImp_k$ = Volume of product $k$ to be imported per hour
- $VolCab_k$ = Volume of product $k$ to be cabotaged per hour
- $RepC$ = Unit reprocessing cost for the slop (US$/m^3$)
- $QCont$ = Uniform cost of quality control for the products entering the pipeline (US$/m^3$)
- $COP$ = Uniform unit penalty cost for violating safety stocks (US$/m^3$)
- $M_1, M_2, M_3, M_4, M_5$ = Large enough constants used in some constraints for logical purposes

### 2.4.3 Decision variables

We now introduce the decision variables used in the model. For simplicity we will call batch $(p, s, l)$ the batch in position $p$ of the sequence type $s$ that is injected into the pipeline in position $l$.

$$X_{s,l} = \begin{cases} 
1 & \text{if a sequence type } s \text{ is injected in the } l\text{-th position into the pipeline} \\
0 & \text{otherwise}
\end{cases}$$

- $VO_{p,s,l}^k$ = Volume of product $k$ injected in batch $(p, s, l)$ at the origin of the pipeline ($m^3$)
- $VOU_{p,s,l}^k$ = Volume of $VO_{p,s,l}^k$ inside the pipeline that is saleable ($m^3$)
- $VD_{p,s,l}^{k,i}$ = Volume of product $k$ in batch $(p, s, l)$ that will be delivered at point $i$ ($m^3$)
- $VR_{p,s,l}^{k,i}$ = Volume of product $k$ from batch $(p, s, l)$ that remains in the pipeline after supplying demand point $i$ ($m^3$)
- $Inv_{i,s,l}^{1,k}$ = Inventory level of product $k$ at demand point $i$ immediately before batch $(p, s, l)$ arrives ($m^3$)
- $InvF_{i,k}$ = Final inventory level of product $k$ at demand point $i$ at the end of the planning horizon ($m^3$)
- $InvR_{p,s,l}^k$ = Inventory level of product $k$ at the refinery at the start of injection of batch $(p, s, l)$ in the pipeline ($m^3$)
- **VolInt** = Total volume of the interface collected over the planning horizon \((m^3)\)
- **VolKer** = Total volume of the Ker batches over the planning horizon \((m^3)\)
- **SlopTotal** = Total volume that needs reprocessing, i.e., the sum of VolInt and VolKer\((m^3)\)
- **TInj_{p,s,l}** = Time at which batch \((p, s, l)\) is injected into the pipeline \((hr)\)
- **TArr_{p,s,l}^i** = Arrival time of the head of batch \((p, s, l)\) at demand point \(i\) \((hr)\)
- **SSViol_{p,s,l}^i** = Amount of product \(k\) below the safety stock (violation) that is allowed at a cost when batch \((p, s, l)\) arrives at point \(i\) \((m^3)\)
- **RC** = Reprocessing cost for the overall slope collected during the time horizon \((US\$)\)
- **QCC** = Quality control cost for measuring the chemical specifications of the batches entering the pipeline during the time horizon \((US\$)\)
- **PC** = Penalty cost for letting inventory levels drop below safety stocks \((US\$)\)
- **TC** = Overall monthly cost: penalty, quality control and reprocessing \((US\$)\)

### 2.4.4 Constraints

1. At each sequencing position \(l\) at most one type of sequence can be assigned
   \[
   \sum_{s \in S} X_{s,l} \leq 1 \quad \forall l \in L
   \]

2. If no sequence is assigned to position \(l\), then no sequence can be assigned to position \(l + 1\)
   \[
   \sum_{s' \in S} X_{s',l+1} \geq X_{s,l} \quad \forall s \in S, l \in L, l < |L|
   \]

3. The volume of product \(k\) in batch \((p, s, l)\) has lower and upper bounded due to operational reasons
   \[
   Pos_{p,s,k} \cdot X_{s,l} \cdot Vmin_{s,p} \leq VO_{p,s,l}^k \leq Pos_{p,s,k} \cdot X_{s,l} \cdot Vmax_{s,p} \quad \forall (p, s, l), \forall k \in K
   \]

4. No volume from batch \((p, s, l)\) can be delivered at point \(i\) if sequence \(s\) is not assigned to position \(l\)
   \[
   VD_{p,s,l}^k \leq M_1 \cdot X_{s,l} \quad \forall (p, s, l), \forall k, i
   \]

5. Lower bounds on the volume delivered at client \(i\) are
   \[
   VD_{p,s,l}^k \geq VSm\min_{i,s,p} \cdot Pos_{p,s,k} \cdot X_{s,l} \quad \forall (p, s, l), \forall i, \forall k \in K_s
   \]

6. Immediately after injection, the saleable part of \(VO_{p,s,l}^k\) may be increased by product upgrading, decreased by product downgrading and/or by the interface with kerosene
   \[
   VOU_{p,s,l}^k \leq VO_{p,s,l}^k + (DV_{p,s} - IntVol_{p,s}) \cdot X_{s,l}, \forall (p, s, l), \forall k \in K
   \]
7. The amounts delivered to clients are taken from saleable products
\[ \sum_{i \in I} VD_{p,s,l}^{k,i} \leq VOU_{p,s,l}^{k}, \forall (p, s, l), \forall k \in K \]

8. The demand of each client must be satisfied
\[ HInv_{i,k} + \sum_{p \in P} \sum_{s \in S} \sum_{l \in L} VD_{p,s,l}^{k,i} = dem_{i,k} + InvF_{i,k}, \forall i, \forall k \in K \]

**Flow conservation constraints**

9. The volume of product \( k \) in batch \((p, s, l)\) that is not going to be delivered in Chillan and will go downstream in the pipeline is
\[ VR_{p,s,l}^{k,Chi} = VO_{p,s,l}^{k} - VD_{p,s,l}^{k,Chi}, \forall (p, s, l), \forall k \in K \]

10. The volume of product \( k \) in batch \((p, s, l)\) that is not going to be delivered in Linares and will go downstream in the pipeline is
\[ VR_{p,s,l}^{k,Lin} = VR_{p,s,l}^{k,Chi} - VD_{p,s,l}^{k,Lin}, \forall (p, s, l), \forall k \in K \]

**Balancing the volumes of interface and slop collected in San Fernando**

11. \( Ker \) separator batches can only be delivered in San Fernando where they will be taken by truck to the refinery for reprocessing
\[ \sum_{i \neq SF} VD_{p,s,l}^{Ker,i} = 0, \forall (p, s, l) \]

12. The overall slop volume generated by the interfaces
\[ VolInt = \sum_{l \in L} \sum_{s \in S} \sum_{p \in P} IntVol_{p,s} \cdot X_{s,l} \]

13. The overall slop volume generated by the kerosene batches
\[ VolKer = \sum_{l \in L} \sum_{s \in S} \sum_{p \in P} VD_{p,s,l}^{Ker, SF} \]

14. The overall slop volume is
\[ SlopTotal = VolInt + VolKer \]

**Injection time constraints**
15. The time of injection of batch \((p, s, l)\) depends on the decision of selecting, or not, a sequence type \(s\) in position \(l\)

\[T_{Inj_{p,s,l}} \leq M_2 \cdot X_{s,l}, \forall (p,s,l)\]

16. The time of injection of the batch in first position in the first sequence to enter the pipeline is

\[T_{Inj_{p_1,s,l_1}} = 0, \forall s\]

17. The injection times of consecutive batches in the same sequence depend on each other

\[T_{Inj_{p,s,l}} \geq T_{Inj_{p-1,s,l}} + \frac{\sum_{k \in K} VO^{k}_{p-1,s,l}}{Flow_{Ref,Ch_i}} , \forall (p,s,l) \mid p > 1\]

18. The injection time of the first batch of a sequence depends on the injection time of the last batch of the previous sequence

\[T_{Inj_{p_1,s',l+1}} \geq T_{Inj_{p,s,l}} + \frac{\sum_{k \in K} VO^{k}_{p,s,l}}{Flow_{Ref,Ch_i}} - M_3(1 - X_{s,l}^{l+1}), \forall p,s,s',l \mid < |L|\]

**Arrival time at a destination point**

19. The time at which batch \((p, s, l)\) arrives at Chilan is greater than or equal to than that of its injection at the origin of the pipeline, plus the time spent in the pipeline segment from there to Chilan

\[T_{Arr_{Ch_i}^{p,s,l}} \geq T_{Inj_{p,s,l}} + \frac{V_{Seg_{Ref,Ch_i}}}{Flow_{Ref,Ch_i}} - M_4(1 - X_{s,l}), \forall (p,s,l)\]

20. The time at which batch \((p, s, l)\) arrives at demand point \(i + 1\) is greater than or equal to that of its arrival at demand point \(i\), plus the time spent in the pipeline segment from \(i\) to \(i + 1\)

\[T_{Arr_{i+1}^{p,s,l}} \geq T_{Arr_{i}^{p,s,l}} + \frac{V_{Seg_{i+1}}}{Flow_{i+1}} - M_5(1 - X_{s,l}), \forall (p,s,l), \forall i \in \{Ch_i, Lin\}\]

**Inventory Constraints**

21. As was detailed in the first sections of the paper, the inventory of product \(k\) at the refinery over time goes up by the production at the refinery itself and the imported amount of that product. It goes down by: the loading of trucks, the loading of cabotage vessels and the injections into the pipeline. These injections are the focus of this study (see Figure 2.2). To summarize, the inventory of product \(k\) at the refinery when batch \((p, s, l)\) starts its injection at time \(T_{Inj_{p,s,l}}\) into the pipeline satisfies the following equation \((m^3)\):

\[InvR_{p,s,l} = InvR_0 + (prod_k + VolImp_k) \cdot T_{Inj_{p,s,l}} - (VolCab_k + tf_k) \cdot T_{Inj_{p,s,l}} - \left[\sum_{l' < l} \sum_{s'} \sum_{p'} VO^{k}_{p',s',l'} + \sum_{p' < p} VO^{k}_{p',s,l}\right];\]

\[\forall (p, s, l), \forall k \in K_s\]
22. The inventory level of product $k$ at client $i$ when batch $(p, s, l)$ arrives is equal to the initial stock plus the collection of all the amounts of product $k$ delivered in the sequences previous to sequence $l$, as well as in the same sequence if it has more than one position for product $k$.

$$\text{Inv}_{p,s,l}^{i,k} = \text{Inv}_{i,k} + \left[ \sum_{l' < l} \sum_{p'} \sum_{s'} VD_{p',s',l'}^{k,i} + \sum_{p' < p} \sum_{s'} VD_{p',s',l}^{k,i} \right] - T\text{Arr}_{p,s,l}^{i} \cdot \text{dem}_{h_{i,k}} \quad \forall (p,s,l), \forall i, \forall k \in K_s$$

23. There is a lower bound on the inventory level of product $k$ at demand point $i$ when batch $(p, s, l)$ arrives

$$\text{Inv}_{p,s,l}^{i,k} \geq SS_{i,k} - SSViol_{p,s,l}^{k,i}, \quad \forall (p,s,l), \forall i, \forall k \in K_s$$

24. One must schedule the arrival of batch $(p, s, l)$ at demand point $i$ so as to prevent a stockout of every product $k$ in that sequence.

$$SSViol_{p,s,l}^{k,i} < SS_{i,k}, \quad \forall (p,s,l), \forall i, \forall k \in K_s$$

25. The inventory level of product $k$ at client $i$ at the end of the time horizon must satisfied given upper and lower bounds

$$\text{FInvMin}_{i,k} \leq \text{Inv}_{i,k} \leq \text{FInvMax}_{i,k}, \quad \forall i, \forall k \in K_s$$

26. If the last saleable batch in sequence $s$ in position $l$ matches the first batch in sequence $s'$ in position $l + 1$, it is not necessary to put a Ker batch between them:

$$VO_{p,s,l}^{Ker} \leq Vmax_{s,p}(2 - X_{s,l} - X_{s',l+1}), \quad \forall (p,s,l), \forall s', l < |L|, L_{p,s} = 1 \text{ and } m_{s,s'} = 1$$

27. Finally, we define the nature of the decision variables

$$X_{s,l} \in \{0,1\}, \forall s,l
VO_{p,s,l}^{k}, VOU_{p,s,l}^{k}, VR_{p,s,l}^{k,i}, VD_{p,s,l}^{k,i}, InvP_{p,s,l}^{k,i}, Inv_{p,s,l}^{i,k}, Inv_{i,k} \geq 0, \forall (p,s,l), \forall i, k
SSViol_{p,s,l}^{k,i}, VolInt, VolKer, SlopTotal, TInv_{p,s,l}, TArr_{p,s,l}^{i} \geq 0, \forall (p,s,l), \forall i, k
RC, QCC, PC, TC \leq 0, \forall (p,s,l), \forall i, k$$

2.4.5 Objective function structure

1. The reprocessing cost $RC$ for the overall slop collected during the time horizon is

$$RC = (VolKer + VolInt) \cdot \text{RepC}$$
2. The quality control cost $QCC$ for measuring the chemical specifications of all the batches entering the pipeline during the time horizon is

$$QCC = \sum_{l \in L} \sum_{s \in S} \sum_{p \in P} \sum_{k \in K} VO_{p,s,l}^k \cdot QCont$$

3. The penalty cost $PC$ for inventory levels below the safety stocks is

$$PC = \sum_{l \in L} \sum_{s \in S} \sum_{p \in P} \sum_{i \in I} \sum_{k \in K} SSV_{iol}^{k,i} \cdot COP$$

We are minimizing $TC$, the overall monthly operational (penalty and quality control) and reprocessing cost for the pipeline:

$$TC = RC + QCC + PC$$
2.5 Implementation of the model at ENAP

The mathematical model described in the previous section was, as stated above, coded in GAMS 24.4.6 using CPLEX 16.2 as a solver. In terms of the options in GAMS-CPLEX for the prioritization in the branch and bound algorithm, a balance between optimality and feasibility was chosen. The Windows machine used to run the code was a Dell XPS Core i7 with 8GB RAM, a 2.4 GHz processor and a solid state drive.

For illustrative purposes throughout this section we describe the data used to run the model for April 2016. The monthly aggregated demand for the 6 products was about 150,000 m$^3$. In the optimal solution the injection of 8 sequences was required to fulfill it. As a reminder, in the case of Chillan, the monthly demands are known but only estimated information about storage capacity, initial inventories and safety stock is available. Indeed a client runs that facility and ENAP is not responsible for managing its inventory. In this location ENAP is only responsible for delivering the monthly demand as homogeneously as possible according to the monthly agreements.

2.5.1 Monthly demand of product $k$ at client $i$ ($dem_{i,k}$)

In Table 2.1 the monthly demand for April 2016 is detailed. The most important product is Die with more than 50% of the entire volume.

<table>
<thead>
<tr>
<th></th>
<th>G93</th>
<th>G97</th>
<th>Die</th>
<th>Kdom</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chillan</td>
<td>15,121</td>
<td>6,822</td>
<td>35,796</td>
<td>2,700</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Linares</td>
<td>7,249</td>
<td>1,797</td>
<td>13,353</td>
<td>900</td>
<td>0</td>
<td>1,900</td>
</tr>
<tr>
<td>San Fernando</td>
<td>18,011</td>
<td>7,900</td>
<td>29,603</td>
<td>428</td>
<td>1,500</td>
<td>5,800</td>
</tr>
<tr>
<td>Total</td>
<td>40,381</td>
<td>16,609</td>
<td>78,752</td>
<td>4,020</td>
<td>1,500</td>
<td>7,700</td>
</tr>
</tbody>
</table>

Table 2.1: Demand in m$^3$ for April 2016

It is important to note that the demand for domestic kerosene ($Kdom$) is highly seasonal. There are months, like the one above, with low demand, but during the winter season the monthly demand in the whole system could be as much as 12,000 m$^3$.

2.5.2 Capacity of product $k$ at client $i$ ($Cap_{i,k}$)

ENAP owns the tanks and distribution centers in Linares and San Fernando. As can be seen in Table 2.2 for gasolines and diesel, San Fernando is the location with the largest storage capacity.

<table>
<thead>
<tr>
<th></th>
<th>G93</th>
<th>G97</th>
<th>Die</th>
<th>Kdom</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linares</td>
<td>7,900</td>
<td>4,300</td>
<td>8,500</td>
<td>2,500</td>
<td>0</td>
<td>1,430</td>
</tr>
<tr>
<td>San Fernando</td>
<td>18,500</td>
<td>18,500</td>
<td>18,500</td>
<td>1,470</td>
<td>2,400</td>
<td>2,200</td>
</tr>
</tbody>
</table>

Table 2.2: Tank capacity in m$^3$ at each demand point of the network
2.5.3 Initial inventory level of product $k$ at client $i$ ($Inv_{i,k}$)

The inventory levels at the start of April 2016 are detailed for Linares and San Fernando in Table 2.3

<table>
<thead>
<tr>
<th></th>
<th>G93</th>
<th>G97</th>
<th>Die</th>
<th>Kdom</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linares</td>
<td>1,500</td>
<td>650</td>
<td>2,050</td>
<td>340</td>
<td>0</td>
<td>315</td>
</tr>
<tr>
<td>San Fernando</td>
<td>4,250</td>
<td>2,250</td>
<td>4,250</td>
<td>335</td>
<td>430</td>
<td>1,300</td>
</tr>
</tbody>
</table>

*Table 2.3: Initial inventory levels in m$^3$ at each demand point*

At Linares and San Fernando the product is pumped from the pipeline to ENAP’s tanks, therefore the initial inventory levels at these points will influence the decisions relative to the first couple of sequences entering into the pipeline.

2.5.4 Safety stock of product $k$ at demand point $i$ ($SS_{i,k}$)

ENAP typically has more than one tank allocated per product at a given demand point. Based on that, it is more accurate to relate the safety stock ($SS$) to the total capacity per product at each demand point. As a general policy, ENAP used to require that the total inventory per product at each demand point at any moment should be sufficient to cover the weekly consumption.

In the new system we structured the analysis recalling the classic continuous review inventory model. That is, assuming a normal distribution of the demand during lead time $L$, the safety stocks are computed as $SS = z\sigma\sqrt{L}$, where $z$ represents the number of standard deviation related with the service quality and $\sigma$ the standard deviation on the demand per unit of time. In our case, we used $z = 2$ which represents 97% fulfilment of demand.

For each demand point, $L$ was estimated as the average delivery time on the pipeline from the refinery. Based on this last approach and the new way of doing the scheduling, ENAP was able to run the operation with lower stocks and fewer stockouts than before.

In Table 2.4 we describe the safety stocks per product at each ENAP point under the new setting.

<table>
<thead>
<tr>
<th></th>
<th>G93</th>
<th>G97</th>
<th>Die</th>
<th>Kdom</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linares</td>
<td>1,500</td>
<td>400</td>
<td>1,700</td>
<td>200</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>San Fernando</td>
<td>3,400</td>
<td>1,500</td>
<td>3,550</td>
<td>100</td>
<td>242</td>
<td>1,187</td>
</tr>
</tbody>
</table>

*Table 2.4: Safety stocks in m$^3$ at each demand point*
2.5.5 Optimal Solution: Injections scheduling

The optimal solution displayed in Table 2.5 shows the eight sequences needed to fulfill the monthly demand based on the set \( \{S_1, \ldots, S_4\} \) defined in Figure 2.3. In addition, we see the day and time at which each batch of each sequence is injected into the pipeline. For instance, the 3rd batch of the 4th sequence is injected in day 5.39, which means on day 6 at 9:22 AM, approximately.

<table>
<thead>
<tr>
<th>Order</th>
<th>Sequence</th>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( p_3 )</th>
<th>( p_4 )</th>
<th>( p_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_1 )</td>
<td>( S_3 )</td>
<td>0.0</td>
<td>0.18</td>
<td>0.27</td>
<td>6.36</td>
<td>0.45</td>
</tr>
<tr>
<td>( l_2 )</td>
<td>( S_4 )</td>
<td>0.58</td>
<td>1.66</td>
<td>1.75</td>
<td>2.84</td>
<td>0.66</td>
</tr>
<tr>
<td>( l_3 )</td>
<td>( S_2 )</td>
<td>2.85</td>
<td>3.02</td>
<td>3.38</td>
<td>3.57</td>
<td>0.89</td>
</tr>
<tr>
<td>( l_4 )</td>
<td>( S_1 )</td>
<td>3.58</td>
<td>5.38</td>
<td>5.39</td>
<td>5.57</td>
<td>6.09</td>
</tr>
<tr>
<td>( l_5 )</td>
<td>( S_3 )</td>
<td>6.92</td>
<td>8.00</td>
<td>8.19</td>
<td>10.73</td>
<td>0.66</td>
</tr>
<tr>
<td>( l_6 )</td>
<td>( S_1 )</td>
<td>10.74</td>
<td>11.82</td>
<td>12.14</td>
<td>12.29</td>
<td>12.89</td>
</tr>
<tr>
<td>( l_7 )</td>
<td>( S_1 )</td>
<td>12.81</td>
<td>15.13</td>
<td>15.14</td>
<td>15.85</td>
<td>18.04</td>
</tr>
<tr>
<td>( l_8 )</td>
<td>( S_1 )</td>
<td>21.05</td>
<td>22.14</td>
<td>22.52</td>
<td>24.34</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5: Injection schedule in the optimal solution for April 2016, where \( p_i \) denotes batch \( i \) in each sequence

2.5.6 Total volume transported

Table 2.6 shows for each product the total volume in \( m^3 \) that was scheduled to be injected at the origin of the pipeline for April 2016 and how this volume was allocated among the demand points. The last column represents the slop volume collected for reprocessing.

<table>
<thead>
<tr>
<th>Product</th>
<th>Volume</th>
<th>Chillan</th>
<th>Linares</th>
<th>San Fernando</th>
<th>Slop</th>
</tr>
</thead>
<tbody>
<tr>
<td>G95</td>
<td>36,343</td>
<td>13,345</td>
<td>7,562</td>
<td>15,324</td>
<td>112</td>
</tr>
<tr>
<td>G97</td>
<td>14,948</td>
<td>5,827</td>
<td>3,478</td>
<td>5,596</td>
<td>48</td>
</tr>
<tr>
<td>Die</td>
<td>70,877</td>
<td>33,868</td>
<td>11,355</td>
<td>25,523</td>
<td>132</td>
</tr>
<tr>
<td>Kdom</td>
<td>3,618</td>
<td>2,891</td>
<td>0</td>
<td>559</td>
<td>68</td>
</tr>
<tr>
<td>C3</td>
<td>1,350</td>
<td>0</td>
<td>0</td>
<td>1,262</td>
<td>88</td>
</tr>
<tr>
<td>C4</td>
<td>6,930</td>
<td>0</td>
<td>1,717</td>
<td>5,213</td>
<td>0</td>
</tr>
<tr>
<td>Ker</td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.6: Volumes injected, distributed and to be reprocessed as slop in \( m^3 \) during the time horizon

2.5.7 Detailed optimal schedule for April 2016

Table 2.7 shows the detailed schedule for April 2016. For instance, the 4th sequence entering the pipeline was type \( S_1 \), with a first batch of 10,000 \( m^3 \) of \( \text{Die} \) that was injected on April 4th at 13:49 and finished on April 6th at 9:07. This batch was split into 2,803 \( m^3 \) for Chillan, 2,102 \( m^3 \) for Linares and 5,083 \( m^3 \) for San Fernando. At the end of the pipeline, a slop volume of 21 \( m^3 \) was collected for reprocessing.
<table>
<thead>
<tr>
<th>Sequence type</th>
<th>Product</th>
<th>Volume (m³)</th>
<th>Injection start</th>
<th>Injection end</th>
<th>Chillan</th>
<th>Linare</th>
<th>San Fernando</th>
<th>Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>C₂</td>
<td>14000</td>
<td>April 1, 04:21</td>
<td>April 1, 06:21</td>
<td>400</td>
<td>200</td>
<td>518</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>C₄</td>
<td>5000</td>
<td>April 1, 06:31</td>
<td>April 1, 08:42</td>
<td>456</td>
<td></td>
<td>44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₅</td>
<td>5000</td>
<td>April 1, 08:42</td>
<td>April 1, 10:52</td>
<td>500</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KM</td>
<td>154</td>
<td>April 1, 10:52</td>
<td>April 1, 12:38</td>
<td>400</td>
<td>200</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>Kev</td>
<td>30</td>
<td>April 1, 12:38</td>
<td>April 1, 13:45</td>
<td></td>
<td>30</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>S₂</td>
<td>DiC</td>
<td>6000</td>
<td>April 1, 13:45</td>
<td>April 1, 15:50</td>
<td>2,000</td>
<td>3,780</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kdom</td>
<td>900</td>
<td>April 2, 15:50</td>
<td>April 2, 18:00</td>
<td>444</td>
<td></td>
<td>0</td>
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Table 2.7: Detailed schedule for April 2016

### 2.6 Implementation and graphical user interface (GUI) for ENAP

While developing the mathematical model, we had a significant interaction with the pipeline schedulers at ENAP. As a consequence we understood better the kind of graphical and numerical information that would be useful to them. The GUI that we built also allows the user easily enter the main parameters of the model before each run.

When the user sets the parameters and presses the link to GAMS in the GUI, an Excel macro will run GAMS-CPLEX in the background and will print the results of the optimal schedule. These results are presented in different ways that we developed after hours of discussions with the schedulers. A trial period allowed the users to interact with the tool, find errors or inconsistencies that are to be expected in a system created in-house from scratch. In the first couple of weeks the users asked many questions and made useful comments and we addressed their concerns to their satisfaction. We continue to have monthly meetings in which we check the status of the model, update
parameters and add new features if necessary.

2.6.1 Computational times

Based on the experience of running the model for over than 18 months, we found as a best way for running the model the following. If after running the model for one hour, no optimal solution has been reached, we stopped the run at a 1% gap. In 95% of the instances, we obtained an optimal solution in less than 25 minutes.

2.7 Impact of the model and cost savings

The two main economic impacts brought by the model came from savings in reprocessing costs for the total slop volume and savings due to a better fulfillment of monthly committed volumes, thus reduced contractual penalties.

2.7.1 Savings in reprocessing cost

Before using our model, on average ENAP used to collect 1,500 $m^3$ of slop per month (average data from 2013-2015). After implementing our system, ENAP currently collects only around 750 $m^3$ (average data from 2016), that is a reduction in the order of 50%.

2.7.2 Savings in contractual penalties for ENAP

These penalties are associated with letting the inventory level going below the safety stock. The use of the model is allowing an approximate annual reduction of 8% in fines as the better scheduling allows to decrease unfulfilled orders.

So, overall the economical annual impact adding savings in reprocessing cost and reduced fines is a reduction of approximately 10% in the overall operational cost of the pipeline. For confidentiality reasons, we are not allowed to provide more details on the savings.

2.8 Another positive effect

Another crucial aspect not measurable in monetary terms is the client’s goodwill. A client that is being supplied on a regular basis tends to be loyal to its supplier. The way that clients show their loyalty is by signing annual supplying contracts with ENAP. It
is important to note that the Chilean fuel market is an open one and every distributor also has the option of importing refined products from other foreign providers. In particular, 30% of the national demand for diesel is being fulfilled by direct imports. A good quality of service is vital for keeping customers. The use of the system has reduced the stockouts to downstream clients, but we have not measured in an exact form this improvement.

2.8.1 Use of the model for evaluating a new way of supplying jet fuel to Maipu

Up to here, we considered that San Fernando was the last demand point on the pipeline. However, there is a segment of the pipeline that goes from San Fernando to Maipu in the Metropolitan region. Maipu is usually supplied by a different pipeline, $P_2$, (see Figure 2.6), which goes from the port of Quintero to the ENAP facility in Maipu. However the BioBio refinery is the only one that produces jet fuel in significant amounts. In order to fulfill Maipu’s demand of jet fuel there are two ways:

i) Loading a vessel in the San Vicente port, near the BioBio refinery and send the vessel to the Quintero port, where the jet fuel is unloaded to take it to Maipu through $P_2$.

ii) Injecting the jet fuel at the BioBio refinery and using the regular pipeline and the extra segment to deliver it to Maipu. The pipeline has the capacity to handle this extra load.

The first choice is the one that was used most of the time. On the other hand, the present model shows that using choice ii) the costs could be reduced in 25%. Considering that monthly demand of jet fuel in Maipu is about 20,000 $m^3$, this alternative gives ENAP a good opportunity for savings.

Based of this finding, ENAP has used this alternative part of the time in 2016 with good results. In addition to the economic incentive just described, sending the jet fuel to Maipu in the pipeline also freed some capacity on the vessels. This capacity can be used for transporting other products.

![Figure 2.6: Extended pipeline configuration](image)
2.9 Conclusions

We have presented an innovative approach for scheduling a pipeline system to transport fuels. To improve the distribution system through a pipeline for ENAP we built an optimization model and a practical computational tool for the company. The system is allowing savings in the order of 10\% in the operational cost of the pipeline and also allows a better quality of service. One key aspect for achieving this success was the full cooperation and involvement of the ENAP’s Logistic Department. The schedule we computed takes into consideration the main operational and commercial aspects that rule this distribution process. This was possible by integrating the operators of the pipeline in the development of the system. The CEO and the COO of the company were attending the project meetings once a month and that is very rare in a large company like ENAP. This project has been a milestone for the company and was the kickoff of a new stage in the way they do scheduling. The process switched from manual and empirical scheduling to an optimization model that analyzes thousands of potential combinations. The development of a GUI was crucial to make the tool user friendly. The GUI has been a key factor for its success.
Chapter 3

Conclusion

In the first paper of the thesis, we described an innovative approach to solve a complex large scale MIP model for optimizing the scheduling of the fleet of tankers scheduling at ENAP, the state-owned petroleum company in Chile. The first model developed was an exact one which was unsolvable on GAMS-CPLEX. As a consequence, our approach was based on reducing the dimension of the model by creating a list of feasible routes by taking into consideration many operational aspects. As a result we built a more compact and tractable model, which we solve to optimality and use this optimal solution as a hot start to the original model. This strategy is novel in the field of maritime transportation of petroleum products and was implemented with a graphic user interface that runs the optimization model. This strategy is currently saving up to 9% of the operational cost for the fleet in comparison with the previous manual procedure.

In the second paper of the thesis, we presented an original approach for scheduling a pipeline system to transport fuels. To improve the distribution system through a pipeline for ENAP we built an optimization model and a practical computational tool for the company. The mathematical model that captures the logical decisions involved and finds a schedule based in the concept of sequence of feasible products. The system decides which type of sequences to use, in which order and the volume of product in each batch to minimize the operating cost while dealing with the trade-off between having fewer batch interfaces and, on the other hand, satisfy client’s demand. The system is allowing savings in the order of 10% in the operational cost of the pipeline and also allows a better quality of service.

In both projects the development of a GUI was crucial to make the tool user friendly and has been a key factor for its success.
Bibliography


