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Innovative Applications of O.R.

Optimizing the pipeline planning system at the national oil company[☆]

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ABSTRACT

This paper describes the creation, development, implementation and impact of a system optimizing the distribution of petroleum products by pipeline at Empresa Nacional del Petroleo, the state-owned oil company in Chile. Refined oil products are sent via a pipeline from a refinery in the South to terminals located between the refinery and the center of the country. The sequencing of different products needs to be determined. This 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, decision makers, 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. In addition, in case of an operational disruption in the middle of a month, the model is run again after updating the parameters accordingly. Operating cost savings are of the order of 10%.

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 ENAP uses is based on pipelines, the other is based on tankers. In this work we describe an approach developed for the company to rationalize the distribution of some oil products through the main pipeline. This one way 360 km pipeline connects its 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 injected into the pipeline. Ideally, one wants to deliver on time the required quantities to the demand points and to control the amount of polluted mixes that can occur depending on the sequence of products sent through the pipeline. Optimizing these operations can be modelled via mixed-integer linear programming (MILP). 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. The demand of the clients is defined through an annual commercial contract, which establishes a monthly delivery volume per product and specific tolerances (monthly and annual). Because of this contract,

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there are symmetric penalties for both players for either not supplying (ENAP's case) or not taking (client's case) agreed upon quantities. This is particulary important at Chillan where ENAP does not own storage capacity. In Linares and San Fernando, where ENAP owns the stocking tanks, the clients are downstream so the inventory levels at the ENAP's facilities allow some flexibility for complying with agreed upon deliveries.

The six products listed above are injected into the pipeline at the refinery and one must decide, at each change of product, the amount and type of the next product, that is 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 (for gasoline and liquified petroleum gas). If some specific products are injected adjacently into the pipeline, a batch of kerosene must be introduced between the two adjacent batches. 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 reprocessing costs, penalties for failing to deliver products as contracted in Chillan, and artificial penalties in case stocks fall below the established safety stocks in San Fernando and Linares. An equilibrium must be reached in terms of balancing the tradeoff between the amount of mixed kerosene to be reprocessed and the length of batches of saleable products. Being more specific, by sending long batches of single products a smaller number of kerosene batches are needed but a potential stockout of the products that are not being send could happen. On the other hand, by sending short batches of saleable products it is possible to have a better control of the inventory levels and penalties at the demand points, but a bigger number of kerosene batches would be needed. It is important to notice that this pipeline is always filled with products and operating unless there is an interruption for either preventive or corrective maintenance. For mechanical reasons, it is important to keep the flow in the pipeline moving all the time and allow no gaps between consecutive batches.

For decades ENAP used a manual approach for pipeline scheduling, based on experience and intuition. Since 2014 the model developed allowed to improve the decision making process by reducing both reprocessing of products and penalties. The company has been using the model very successfully, generating cost-savings of about 10% compared to previous years. The optimization part of the system uses a commercial code and its use has been facilitated by a user friendly GUI (Graphical user interface) that is used on a regular basis.

The paper is organized as follows. In Section 2 we present a review of the literature related with our work. In Section 3 we describe the pipeline distribution problem at ENAP in a qualitative way. In Section 4 we introduce the general methodology for addressing the problem. In Section 5 we introduce the mathematical model. In Section 6 we describe the actual system implementation at ENAP and the main results obtained. In Section 7 we analyze the process for building the GUI tool for ENAP's schedulers. In Section 8 we discuss the impact of the system for the company. Finally, in Section 9 we draw some conclusions.

2. Related work

The body of literature describing research on pipeline scheduling has been growing since 2000. Although there are several case studies using real data from companies we could not find in the literature evidence of real applications of models in oil and gas companies.

Relvas, Matos, and Fialho (2006) formulated an MILP model based on a continuous-time formulation 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 of building a schedule only for a very short time horizon. A more refined model including inventory constraints is presented by Pinto, Joly, and Moro (2000). Key decisions in this model involve loading and unloading tanks and pipeline operations. It 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, liquified petroleum gas and jet fuel for a short 3-days planning horizon

The complexity of multi-product pipeline scheduling is related with the relationship between binary and continuous decision variables. Rejowski and Pinto (2003) developed a MILP discrete-time optimization models for finding the best order to inject the products, keep track of inventory levels on the depot along the pipeline. Based on this model, the same authors (Rejowski & Pinto, 2004) improve the previous model to minimize the product contamination inside pipeline.

Gleizes, Cafaro, Mendez, Cerda, and Herrero (2012) introduced a discrete event simulation system with several sources in a pipeline network and a system that assigns servers to demands points. Cafaro and Cerda (2004) presented a continuous mathematical model for the multi-product pipeline scheduling problem reducing the calculation time from previous discrete-time attempts.

Later on, Cafaro and Cerda formulated a new version minimizing the total operating cost for different network structures (Cafaro & Cerda 2010; 2011; 2012). For a multi-branch and multi-product pipeline networks, MirHassani et al. proposed a continuous-time scheduling formulation taking into account several pipeline operational constraints (MirHassani & Fani Jahromi, 2011; MirHassani & Ghorbanalizadeh, 2008). MirHassani, Abbasi, and Moradi (2013) developed a MILP continuous-time model for unidirectional pipelines that can deliver and inject products at the same time. This approach resulted in a better approximation for the computation of the interfaces volume generated along the pipeline that need to be reprocessed in comparison with the previous work. Castro (2010) presented a new continuous-time formulation for addressing a complex pipeline network involving several refineries and multiple demand points. Ghaffari and Mostafaei (2015) proposed a MILP formulation for multi-product pipeline in which the mathematical model determines both the optimal injections and delivery schedule in one stage rather than two stages. More recently, Liao, Liang, Xu, Zhang, and Wang (2018) presented an integrated optimization of the pipeline scheduling and pump scheduling through a discrete-time MILP model. In this article the inventory constraints at demand points were not taken into consideration. In contrast, in this paper safety stocks are explicitly tracked in order to protect against demand uncertainty. Meira, Magatão, Relvas, Barbosa Pvoa, and Neves Junior (2017) presented a decomposition approach for a long term scheduling in a single source multiproduct pipeline network and described a case study with data from a company.

By comparison with most references in the literature, our study worked from the bottom up. We started with a specific practical situation that had not been optimized before. Sustained efforts to understand all aspects of the problems required continuous interaction between the main protagonists: modelers and schedulers as well as managers at ENAP, and the authors, directly or indirectly. The project included a study of the current operations, including separating essential from nonimportant details, relative to the operations of the refinery, of the pipeline, of the receiving sites belonging to ENAP and linked to customer tanks, vs those

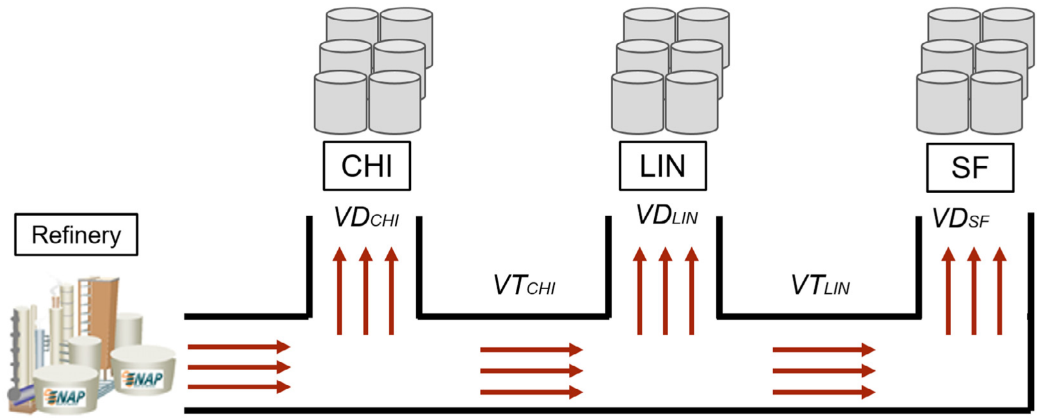

Fig. 1. Pipeline network.

belonging to customers and not controlled by ENAP, and finally of the return to the refinery of product mixes that had to be transported back for reprocessing. Additional concerns considered were the on-time deliveries of finished products at the demand sites, and the sequencing of the individual product injections at the refinery. A careful study of the previous shipping patterns plus an attempt at generating patterns "of interest", that is patterns that were feasible in terms of product sequencing and neither too long nor to short to be practical, yielded a family of initially four, then more recently six basic patterns that are flexible enough and still simple enough to be workable and economical in terms of overall costs. In a given pattern, in some cases, the amount of certain products could be zero, allowing actually a larger set of combinations including smaller chains. While and after deciding on these main tools, still in close cooperation with the schedulers, came the construction of a complex MIP model taking all the above ingredients into account, and still general enough to be applicable to similar situations in other types of environment. This model has been in use at ENAP for several years, allowing a closer control of operations and substantial savings for the company.

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.
- Based on nearly two years of close interaction with the expert at the Logistics Department and pipeline operators we managed to truly identify the key and essential drivers of the operation. Therefore we were able to set the level of complexity that really is worth including in an optimization model for making the end product a trusted decision making tool for the company.

3. The pipeline system at ENAP and problem description

ENAP uses a 360 km pipeline that starts at ENAP's BioBio Refinery (ERBB) and goes north. It has 3 demand points, from south to north, Chillan (Chi), Linares (Lin) and San Fernando (SF) as shown in Fig. 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. For the demand points in this pipeline network, on average, ENAP's monthly demand is approximately 150,000 cubic meters.

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 Chillan, 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 specified monthly demands as homogeneously as possible. 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 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 times 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 cubic meters, so at least 100 cubic meters 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 specify the demand per product for the incoming month, which must be among the contractual volumetric tolerance levels, and ENAP must build a schedule for the delivery of each product to each client at each demand point. In addition, products must satisfy volume and flow rate constraints in the pipeline.

One feature of this pipeline 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 mixed volume of the adjacent products and must be reprocessed at the refinery unless it can be sold (e.g., G97 mix with G93 it is 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 part of the product that gets contaminated with the *Ker* plus the batch of *Ker* itself 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, 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

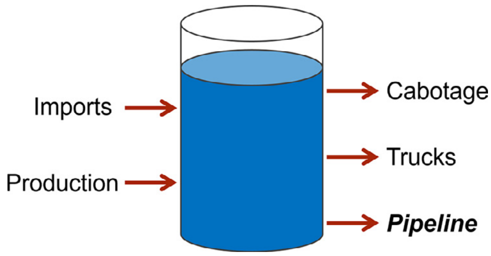

Fig. 2. Inventory dynamics of a tank at the refinery: The level goes up through imports and refinery production and goes down through loading of cabotage vessels, trucks and the pipeline.

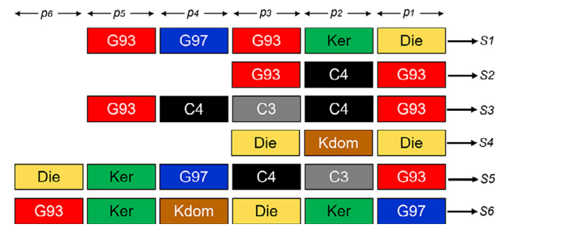

Fig. 3. Describes the 6 types of sequences considered. Each sequence is characterized by its positions $p_1, p_2, \ldots, p_6$. Sequences S_5 and S_6 have 6 positions, S_1 and S_3 have 5 positions and S_2 and S_4 have 3 positions.

sequences and there were often difficulties delivering on time according to the agreed upon schedule. Delays resulted in significant penalty costs 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 penalty and reprocessing costs.

4. 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, 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 Fig. 2 shows, the inventory for each product increases through production at the refinery and direct imports of 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.

Because of their chemical engineering background and long field experience, ENAP's pipeline schedulers know for any pair of products 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 a set of six main types of feasible sequences, i.e., sequences that may be injected into the pipeline and satisfy the chemical constraints (S_1, S_2, S_3, S_4, S_5, S_6). A sequence consists of several batches following each other in a specific order. The complete list of saleable products is: 93 octane gasoline (G93), 97 octane gasoline (G97), diesel (Die), propane (C3), butane (C3) and domestic kerosene (Kdom). The separator product is regular kerosene (Ker).

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 octane gasoline (G93), the fourth is for 97 octane gasoline (G97) and the fifth is for 93 octane gasoline (G93) (see Fig. 3). A crucial decision that the model makes is the order in which the sequences are entering into the pipeline and the volume in each batch of each sequence. 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:

From a pure combinatorial point of view it is clear that the 6 sequences above do not cover all theoretical possibilities. However, from a chemical and operational point of views, they completely satisfy the restrictions and handling of the pipeline at the injection point. Initially we were using a set of 4 sequences, and after further discussions with the experts, we decided to add two other sequences, resulting in minor improvement in the optimal value of the objective function. Adding more sequences however was useless, they neither contributed to the optimum nor did they make technical sense. Indeed every time a new sequence is injected into the pipeline at the refinery, a system of valves must be handled and some manipulation occurs. As far as the company is concerned, the current 6 sequences achieve the desired purpose.

As was mentioned before in the introduction, the role of the batches called *Ker* (not a saleable commodity) is to isolate certain pairs of products by avoiding direct contact between them. In some sequences there are *Ker* batches inside them (S_1, S_5, S_6), in other cases it is necessary to add a *Ker* batch between consecutive sequences (S_2 followed by S_4). However, if the final saleable batch of a sequence is the same as the initial batch of the following sequence, then no *Ker* is needed as a separator. This is the case for S_1 followed by S_2 in Fig. 4. One of the goals of the model is to minimize the monthly volume of *Ker* injected in the pipeline because it has a reprocessing cost.

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, as described in Fig. 1, consider the following example. There is a batch of 3000 cubic meters of G93 to be allocated as follows: 800 cubic meters for Chillan, 1000 cubic meters for Linares and 1200 cubic meters for San Fernando. In addition, a batch of 2000 cubic meters of DIE is to be offloading as follows: 1000 cubic meters for Chillan, 500 cubic meters for Linares and 500 cubic meters for San Fernando (see Fig. 5). Since G93 and DIE are not compatible products (they cannot be in touch with each other) a *Ker* batch must be located between them and collected at the end of the pipeline in San Fernando.

In the previous example, a more accurate description would be as follows. Instead of injecting 2000 cubic meters of DIE at the origin of the pipeline, the right amount would be 2012 cubic meters considering the 12 cubic meters of DIE that are going to be polluted for direct contact with *Ker*. In the same fashion, the right amount of G93 would be 3010 cubic meters taking into account the 10 cubic meters of G93 that are going to be polluted for direct contact with *Ker*. As a consequence instead of collecting 30 cubic meters of *Ker* in San Fernando for reprocessing, the right amount would be 52 cubic meters (30+12+10).

5. The pipeline scheduling optimization model at ENAP

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

5.1. Set definitions

- R = The refinery in BioBio that supplies the pipeline (Ref)
- I = Demand points in the pipeline network (Chi, Lin and SF)

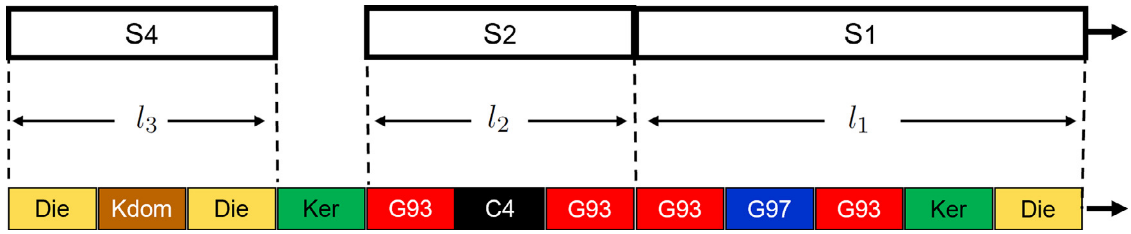

Fig. 4. Example of sequences. A sequence S_1 is the first entering the pipeline, S_2 is the second and S_4 the third.

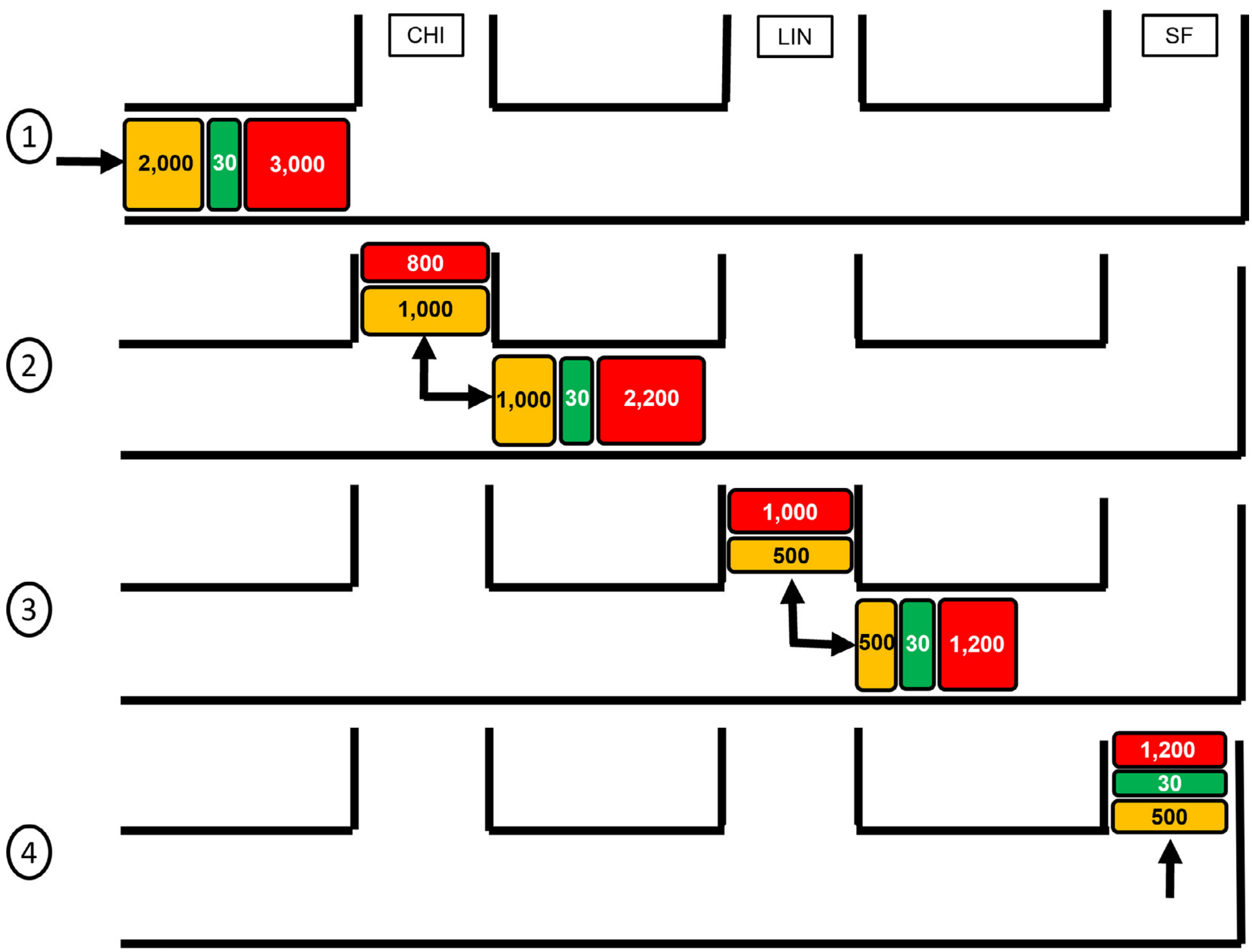

Fig. 5. Splitting a batch. From a batch of 3000 cubic meters of G93 (red), 800 cubic meters are delivered in Chillan, 1000 cubic meters in Linares and 1200 cubic meters in San Fernando. In parallel, from a batch of 2000 cubic meters of DIE (yellow), 1000 cubic meters are offloaded in Chillan, 500 cubic meters in Linares and 500 cubic meters in San Fernando. A batch of *Ker* is located between the original batches and collected in San Fernando. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- K_s= Saleable products: 93 octane gasoline (G93), 97 octane gasoline (G97), diesel (*Die*), domestic kerosene (*Kdom*), 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, S_5, S_6.
- 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 *Kdom* is in second position.
- L = Order of sequences as they enter the pipeline, namely, $l_1, l_2, l_3, \ldots$. For instance, in Fig. 4 the first sequence, l_1, is type S_1, the second sequence, l_2, is type S_2, and the third sequence, l_3, is type S_4. The evidence shows that no more than 15 sequences are needed for a monthly plan horizon.

5.2. Parameters

We now introduce the main parameters used in the model.

- $prod_k$ = Production rate of product k at the refinery (cubic meter per hour)
- tlf_k = Volume of product k to be delivered per hour at the truck loading facility near the refinery (cubic meter per hour)
- $dem_{i,k}$ = Monthly demand for product k at point i (cubic meter)
- $demh_{i,k}$ = Hourly demand, i.e., $dem_{i,k}/720$
- $Cap_{i,k}$ = Tank storage capacity for product k at point i (cubic meter)
- $Flow_{i,j}$ = Recommended rate of flow between consecutive demand points i and j (cubic meter per hour)

- $SS_{i,k}$ = Safety stock of product k at demand point i (cubic meter)
- $Vmin_{s,p}$, $Vmax_{s,p}$ = Minimum (maximum) volume allowed for the product in position p in sequence s (cubic meter)
- $VSmin_{i,s,p}$ = Minimum volume of the product in position p in sequence s to be supplied at demand point i (cubic meter). Defined for operational reasons in order to avoid very little volume delivered.
- μ = Allowable deviation tolerance for the monthly demand fulfilment at Chillan demand point
- $Pos_{p,s,k}$ = 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
- $vaKer_{s,s'}$ = 1, if for chemical reasons a batch of kerosene must be injected between sequences s and s' ; 0, otherwise
- $IntVol_{p,s}$ = Volume of the interface generated in position p of sequence s (cubic meter)
- $DV_{p,s}$ = Degraded/upgraded volume in position p of sequence s (cubic meter). This volume is positive when the volume of the product in position p increases by being mixed with some higher quality product from its neighbors. It is negative when the opposite occurs, i.e., there is a loss due to being mixed with an inferior neighbor product, and zero otherwise.
- $VSeg_{i,j}$ = Capacity of the pipeline segment between consecutive demand points i and j (cubic meter)
- $IInv_{i,k}$ = Initial inventory level of product k at point i (cubic meter)
- $InvR^k_0$ = Initial inventory level of product k at the refinery (cubic meter)
- $FInvMin_{i,k}$, $FInvMax_{i,k}$ = Minimum (maximum) level of inventory of product k needed at point i at the end of the planning horizon (cubic meter)
- $VolImp_k$ = Volume of product k to be imported per hour (cubic meter per hour)
- $VolCab_k$ = Volume of product k sent per hour to the San Vicente port to be distributed by tankers (cubic meter per hour)
- $RepC$ = Unit reprocessing cost for the slop (US$ per cubic meter)
- $QCont$ = Uniform unit cost of quality control for the products entering the pipeline (US$ per cubic meter)
- COP = Uniform unit penalty cost for violating safety stocks (US$ per cubic meter)
- M_1, M_2, M_3, M_4, M_5 = Constants used in some constraints for logical purposes. They were defined taking into account the order of magnitude of the constraint in which they participate.

5.3. 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.

Binary variables

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

$$Y_{s,s',l} = \begin{cases} 1 & \text{if sequence type } s \text{ in the } l\text{th position is followed} \\ & \quad \text{by } s' \text{ in the } l+1\text{th position} \\ 0 & \text{otherwise} \end{cases}$$

Continuous variables

- $VO^k_{p,s,l}$ = Volume of product k injected in batch (p, s, l) at the origin of the pipeline (cubic meter)
- $VOU^k_{p,s,l}$ = Volume of $VO^k_{p,s,l}$ inside the pipeline that is saleable (cubic meter)
- $VD^{k,i}_{p,s,l}$ = Volume of product k in batch (p, s, l) that will be delivered at point i (cubic meter)
- $VR^{k,i}_{p,s,l}$ = Volume of product k from batch (p, s, l) that remains in the pipeline after supplying demand point i (cubic meter)
- $Inv^{i,k}_{p,s,l}$ = Inventory level of product k at demand point i immediately before batch (p, s, l) arrives (cubic meter)
- $InvF_{i,k}$ = Final inventory level of product k at demand point i at the end of the planning horizon (cubic meter)
- $InvR^k_{p,s,l}$ = Inventory level of product k at the refinery at the start of injection of batch (p, s, l) in the pipeline (cubic meter)
- $VolInt$ = Total volume of the interface collected over the planning horizon (cubic meter)
- $VolKer$ = Total volume of the *Ker* batches over the planning horizon (cubic meter)
- $SlopTotal$ = Total volume that needs reprocessing, i.e., the sum of *VolInt* and *VolKer*(cubic meter)
- $TInj_{p,s,l}$ = Time at which batch (p, s, l) is injected into the pipeline (hour)
- $Tarr^i_{p,s,l}$ = Arrival time of the head of batch (p, s, l) at demand point i (hour)
- $SSViol^{k,i}_{p,s,l}$ = Amount of product k below the safety stock (violation) that is allowed at a cost when batch (p, s, l) arrives at point i (cubic meter)
- TRC = Total reprocessing cost for the overall slop collected during the time horizon (*US*$)
- PC = Total penalty cost for injections after the last day of planning month (*US*$)
- TC = Overall monthly cost: penalty and reprocessing (*US*$)

5.4. 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 $l+1$

$$\sum_{s' \in S} X_{s',l} \geq X_{s,l+1} \quad \forall s \in S, l \in L, l < |L|$$

3. The volume of product k in batch (p, s, l) has lower and upper bounded due to operational reasons

$$Pos_{p,s,k} \cdot X_{s,l} \cdot Vmin_{s,p} \leq VO^k_{p,s,l} \leq Pos_{p,s,k} \cdot X_{s,l} \cdot Vmax_{s,p} \quad \forall (p,s,l), \forall k \in K$$

4. No volume from batch (p, s, l) can be delivered at point i if sequence s is not assigned to position l

$$VD^{k,i}_{p,s,l} \leq M_1 \cdot X_{s,l} \quad \forall (p,s,l), \forall k, i$$

5. Lower bounds on the volume delivered at client i

$$VD^{k,i}_{p,s,l} \geq VSmin_{i,s,p} \cdot Pos_{p,s,k} \cdot X_{s,l} \quad \forall (p,s,l), \forall i, \forall k \in K_s$$

6. Immediately after injection, the saleable part of $VO^k_{p,s,l}$ may be increased by product upgrading, decreased by product downgrading and/or by the interface with kerosene

$$VOU^k_{p,s,l} \leq VO^k_{p,s,l} + (DV_{p,s} - IntVol_{p,s}) \cdot X_{s,l}, \quad \forall (p,s,l), \forall k \in K$$

7. The amounts delivered to clients are taken from saleable products

$$\sum_{i \in I} VD^{k,i}_{p,s,l} \leq VOU^k_{p,s,l}, \quad \forall (p,s,l), \forall k \in K$$

8. The total demand at Chillan must be satisfied over the entire planning period. However, a small deviation ($\mu = 7,5\%$) is allowed by commercial contracts.

$$(1-\mu)\cdot dem_{Chi,k} \le \sum_{p\in P}\sum_{s\in S}\sum_{l\in L} VD^{k,Chi}_{p,s,l} \le (1+\mu)\cdot dem_{Chi,k},\quad \forall k\in K_s$$

9. The total demand at Linares and San Fernando points over the entire planning period must be at least satisfied

$$\sum_{p\in P}\sum_{s\in S}\sum_{l\in L} VD^{k,i}_{p,s,l} \ge dem_{i,k},\quad \forall i \ne Chi, \forall k\in K_s$$

Flow conservation constraints

10. 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

$$VR^{k,Chi}_{p,s,l} = VO^{k}_{p,s,l} - VD^{k,Chi}_{p,s,l},\quad \forall (p,s,l), \forall k\in K$$

11. 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

$$VR^{k,Lin}_{p,s,l} = VR^{k,Chi}_{p,s,l} - VD^{k,Lin}_{p,s,l},\quad \forall (p,s,l), \forall k\in K$$

Balancing the volumes of interface and slop collected in San Fernando

12. If sequence type s is not assigned to position l, then the binary variable linking with sequence type s' in position $(l+1)$ must be equal to zero

$$Y_{s,s',l} \le X_{s,l},\quad \forall (s,s',l)$$

13. If sequence type s' is not assigned to position $(l+1)$, then the binary variable linking with sequence type s in position l must be equal to zero

$$Y_{s,s',l} \le X_{s',l+1},\quad \forall (s,s',l)$$

14. If sequence type s is assigned to position l and sequence type s' is assigned to position $(l+1)$ then the binary variable linking them must be equal to one

$$X_{s,l} + X_{s',l+1} \le 1 + Y_{s,s',l},\quad \forall (s,s',l)$$

15. *Ker* separator batches can only be delivered in San Fernando where they will be taken by truck to the refinery for reprocessing

$$\sum_{i\ne SF} VD^{Ker,i}_{p,s,l} = 0,\quad \forall (p,s,l)$$

16. The overall slop volume generated by the kerosene batches

$$VolKer = \sum_{l\in L}\sum_{s\in S}\sum_{p\in P} VD^{Ker,SF}_{p,s,l}$$

17. The overall slop volume generated by the interfaces

$$VolInt = \sum_{l\in L}\sum_{s\in S}\sum_{p\in P} IntVol_{p,s}\cdot X_{s,l}$$

18. The overall slop volume is

$$SlopTotal = VolInt + VolKer$$

Injection time constraints

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

$$TInj_{p,s,l} \le M_2\cdot X_{s,l},\quad \forall (p,s,l)$$

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

$$TInj_{p_1,s,l_1} = 0,\quad \forall s$$

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

$$TInj_{p,s,l} \ge TInj_{p-1,s,l} + \frac{\sum_{k\in K} VO^{k}_{p-1,s,l}}{Flow_{Ref,Chi}},\quad \forall (p,s,l)\quad |\quad p>1$$

22. The injection time of the first batch of a sequence depends on the injection time of the last batch of the previous sequence and whether or not is necessary the injection of a 30 cubic meters *Ker* batch in between

$$TInj_{p1,s',l+1} \ge \left(TInj_{p,s,l} + \frac{\sum_{k\in K} VO^{k}_{p,s,l} + 30\cdot vaKer_{s,s'}}{Flow_{Ref,Chi}} \right) L_{p,s} - M_3(1 - X_{s',l+1}),\quad \forall p,s,s',l | l < |L|$$

Arrival time at a destination point

23. The time at which batch (p, s, l) arrives at Chillan 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 Chillan

$$Tarr^{Chi}_{p,s,l} \ge TInj_{p,s,l} + \frac{VSeg_{Ref,Chi}}{Flow_{Ref,Chi}} - M_4\left(1 - X_{s,l}\right),\quad \forall (p,s,l)$$

24. 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 $i+1$

$$Tarr^{i+1}_{p,s,l} \ge Tarr^{i}_{p,s,l} + \frac{VSeg_{i,i+1}}{Flow_{i,i+1}} - M_5\left(1 - X_{s,l}\right),\quad \forall (p,s,l),\ \forall i\in \{Chi, Lin\}$$

Inventory constraints

25. 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.

$$Inv^{i,k}_{p,s,l} = IInv_{i,k} + \left[\sum_{l'<l}\sum_{p'}\sum_{s'} VD^{k,i}_{p',s',l'} + \sum_{p'<p}\sum_{s'} VD^{k,i}_{p',s',l} \right] - Tarr^{i}_{p,s,l}\cdot demh_{i,k},\qquad \forall (p,s,l), \forall i, \forall k\in K_s$$

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

$$Inv^{i,k}_{p,s,l} \ge SS_{i,k} - SSViol^{k,i}_{p,s,l},\qquad \forall (p,s,l), \forall i, \forall k\in K_s$$

27. There is an upper bound on the volume delivered at each demand point i when batch (p, s, l) arrives

$$VD^{k,i}_{p,s,l} \le Cap_{i,k} - Inv^{i,k}_{p,s,l},\qquad \forall (p,s,l), \forall i, \forall k\in K_s$$

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

$$X_{s,l}\in\{0,1\},\quad \forall s,l$$

$$VO^{k}_{p,s,l}, VOU^{k}_{p,s,l}, VR^{k,i}_{p,s,l}, VD^{k,i}_{p,s,l}, Inv^{i,k}_{p,s,l}, SSViol^{k,i}_{p,s,l} \ge 0,\quad \forall (p,s,l), \forall i,k$$

$$VolInt, TInj_{p,s,l}, TArr^{i}_{p,s,l}, RC, QCC, PC, TC \ge 0,\quad \forall (p,s,l), \forall i,k$$

5.5. Objective function structure

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

$$RC = \left(\sum_{s}\sum_{s'}\sum_{l} Y_{s,s',l}\cdot 30\cdot vaKer_{s,s'} + SlopTotal \right)\cdot RepC$$

Table 1
Key performance measures comparison between 2013, 2014 and 2018.

	Manual planning			Optimized planning					
Performance measure	Oct-13	Nov-13	Dic-13	Jan-14	Feb-14	Mar-14	Jan-18	Feb-18	Mar-18
Volume for reprocessing (cubic meter)	2.040	1.920	1.850	850	790	760	700	715	710
Fulfillment of the demand	85%	87%	86%	94%	94%	95%	97%	98%	98%

2. The quality control cost QCC for measuring the chemical specifications of all the batches entering the pipeline during the time horizon is

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

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

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

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

$$TC = RC + QCC + PC$$

6. Implementation of the model at ENAP

The mathematical model described in the previous section was 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 8 gigabytes RAM, a 2.4 gigahertz processor and a solid state drive.

Table 1 shows a comparison between key performance measures for October, November and December in 2013, previous to the use of the optimization model, and January, February and March in 2014 with the pipeline planning made with the help of the model. In addition, January, February and March in 2018 are presented in order to see the impact of the current version of the model and a more mature and skilled group of schedulers at ENAP. It can be seen that the use of the model in 2014 allowed a reduction of 50% or more in the monthly volume for reprocessing from 2013. In addition, an increment of 8%-10% in the fulfillment of the demand and the corresponding reduction in contractual penalty fees with clients was achieved.

For illustrative purposes throughout this section we describe the data used to run the model for September 2018. The monthly aggregated demand for the 6 products was about 155,000 cubic meters. 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 by contract. The 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. Estimated information about the inventories available allows to define the more convenient dates to deliver the products.

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

In Table 2 the monthly demand for September 2018 is detailed. The most important product is *Die* with more than 50% of the entire volume.

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 cubic meters.

Table 2
Demand in cubic meter for September 2018.

	G93	G97	Die	K Dom	C3	C4
Chillan	20.000	8.100	42.958	1.095	0	0
Linares	6.400	1.600	13.000	0	597	1.440
San Fernando	17.400	8.500	27.400	1.216	2.300	2.638
Total	**43.800**	**18.200**	**83.358**	**2.311**	**2.897**	**4.078**

Table 3
Tank capacity in cubic meter for each product.

	G93	G97	Die	K Dom	C3	C4
Chillan	5.000	3.000	8.665	800	0	0
Linares	8.000	4.000	8.000	2.100	1.400	1.400
San Fernando	18.000	18.000	18.000	900	2.350	2.100

Table 4
Initial inventory levels in cubic meter at each demand point (approximated numbers in the case of Chillan).

	G93	G97	Die	K Dom	C3	C4
Chillan	2.000	2.200	6.800	600	0	0
Linares	4.800	2.400	4.800	400	700	715
San Fernando	9.600	9.600	9.600	800	1.200	1.100

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

ENAP owns the tanks and distribution centers in Linares and San Fernando. Table 3 shows the storage capacity for each product in each location.

6.3. Initial inventory level of product k at client i ($IInv_{i,k}$)

The inventory levels at the start of September 2018 for Linares and San Fernando are detailed in Table 4

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.

6.4. Safety stock of product k at demand point i (SS^{k}_{i})

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_i, 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 σ the standard deviation on the demand per unit of time. In our case, we used $z = 2$ which represents 97% fulfilment of demand (Figs. 6 and 7).

For each demand point i, the lead time L_i was estimated as the transit time of the flow on the pipeline from the refinery to

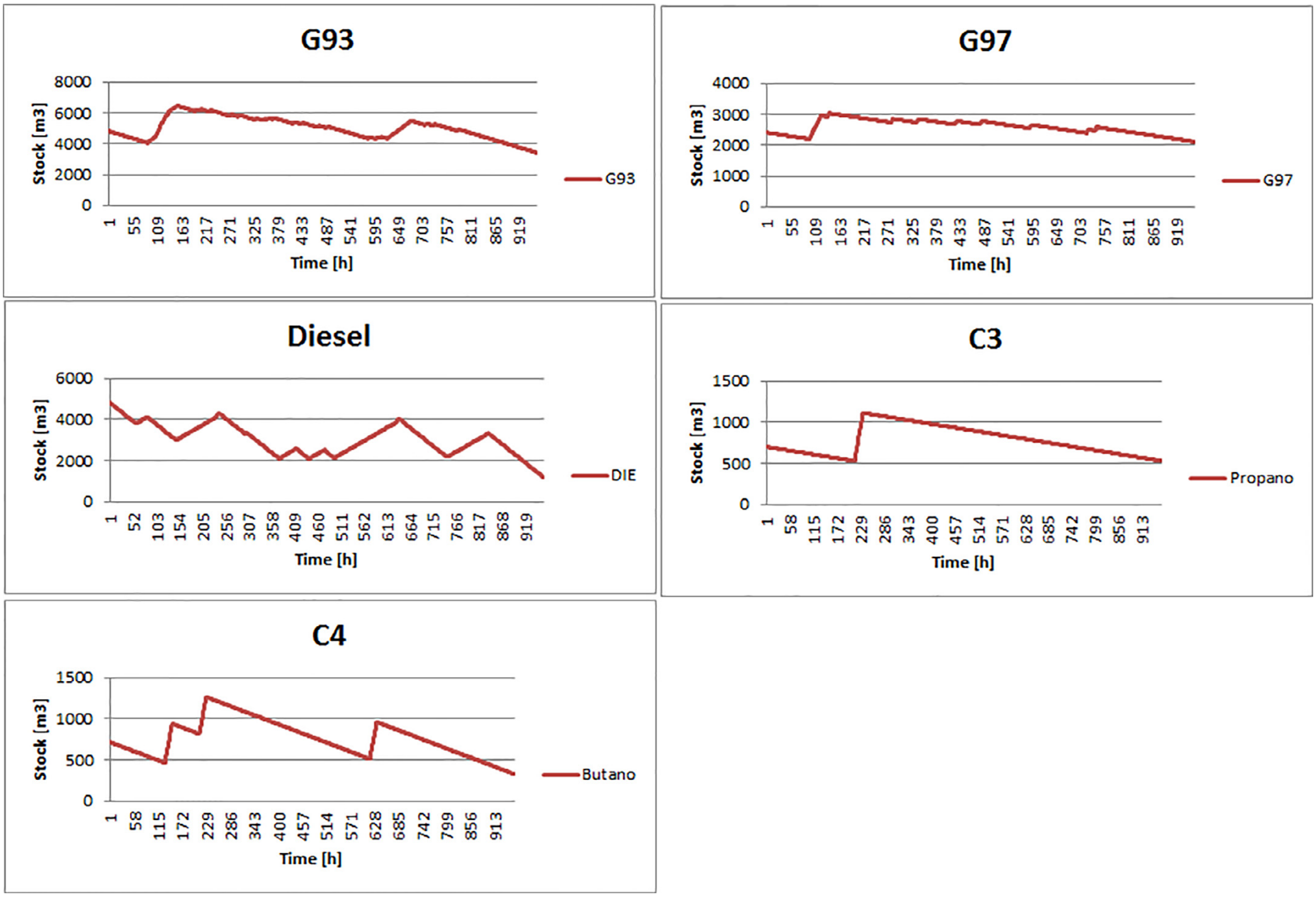

Fig. 6. Stock levels at Linares.

Table 5
Safety stocks in cubic meter at each demand point (approximated numbers in the case of Chillan).

	G93	G97	Die	K Dom	C3	C4
Chillan	500	400	1.600	200	0	0
Linares	1.000	500	2.000	200	0	123
San Fernando	1.500	500	2.000	250	242	187

point *i*. 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 5 we describe the safety stocks per product at each ENAP point under the new setting.

6.5. Optimal solution: Injections scheduling

The optimal solution displayed in Table 6 shows the thirteen sequences needed to fulfill the monthly demand based on the set $\{S_1, \ldots, S_6\}$ defined in Fig. 3. In addition, the table shows 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 **6.55**, which means on day 7 at 13:07 PM. approximately.

6.6. Total volume transported

Table 7 shows for each product the total volume in cubic meter that was scheduled to be injected at the origin of the pipeline for September 2018 and how this volume was allocated among the demand points. The last column represents the slop volume collected for reprocessing.

Table 6
Injection schedule in the optimal solution for September 2018, where p_i denotes batch *i* in each sequence.

Order	Sequence	*p1*	*p2*	*p3*	*p4*	*p5*	*p6*
I1	*s1*	0.00	1.22	1.23	1.59	1.96	
I2	*s3*	2.32	2.69	2.79	3.03	3.13	
I3	*s6*	3.31	3.72	3.73	5.35	5.66	5.67
I4	*s3*	6.08	6.44	**6.55**	6.91	7.01	
I5	*s1*	7.39	8.88	8.89	9.25	9.66	
I6	*s1*	10.03	11.25	11.26	11.62	12.03	
I7	*s2*	12.39	12.76	12.86			
I8	*s1*	13.23	14.80	14.81	15.17	15.58	
I9	*s1*	15.95	17.16	17.17	17.54	17.95	
I10	*s1*	18.32	21.81	21.82	22.19	22.60	
I11	*s2*	22.96	23.33	23.65			
I12	*s1*	24.02	27.16	27.17	27.54	27.95	
I13	*s6*	28.31	28.72	28.73	30.04	30.18	30.19

6.7. Detailed optimal schedule for September 2018

Tables 8 and 9 show the detailed schedule for September 2018. For instance, the 8th sequence entering the pipeline was type S_1, with a first batch of 7696 cubic meters of *Die* that was injected on September 14th at 05:34 and finished on September 15th at 19:07. This batch was split into 4147 cubic meters for Chillan, 1138 cubic meters for Linares and 2399 cubic meters for San Fernando. At the

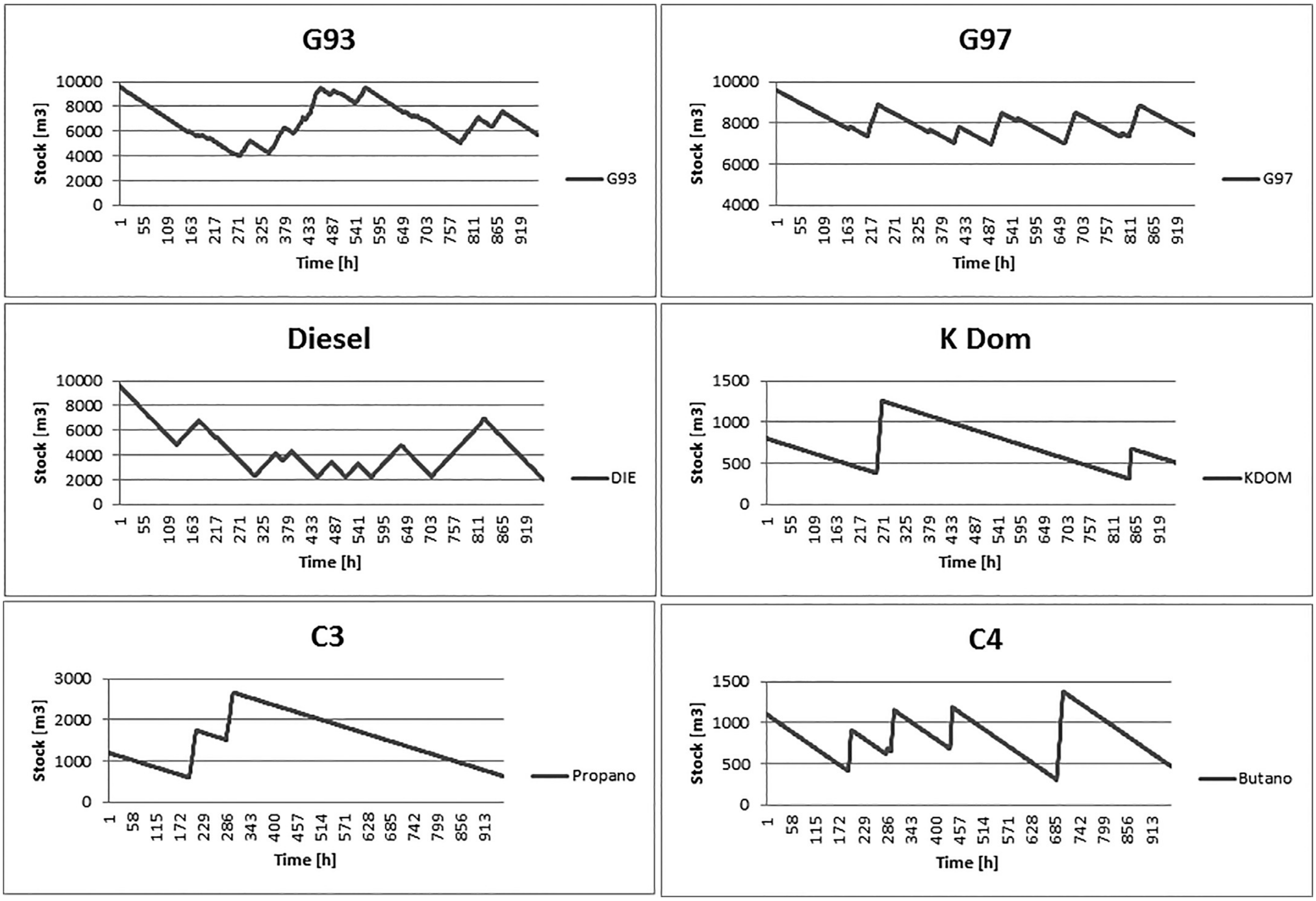

Fig. 7. Stock levels at San Fernando.

Table 7
Volumes injected, distributed and to be reprocessed as slop in cubic meter during the time horizon.

Product	Volume (cubic meter)	Chillan	Linares	San Fernando	Slop
G93	**42,683**	18,771	6400	17,400	112
G97	**17,809**	7493	1600	8500	217
Die	**80,220**	39,736	13,000	27,400	84
K Dom	**2229**	1013	0	1216	0
C3	**2985**	0	597	2300	88
C4	**4078**	0	1440	2638	0
Ker	**330**	0	0	330	0

end of the pipeline, a slop volume of 12 cubic meters was collected for reprocessing.

6.8. Stock levels

The following curves describe the inventory levels at the ENAP facilities. In the case of Linares, they show the inventory for each product over the planning horizon.

Similarly, the following curves describe the inventory levels at San Fernando, for each product, over the planning horizon

7. 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 to easily enter the main parameters of the model before each run.

After the user sets up 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.

7.1. Computational times

Based on the experience of running the model for over 18 months, we found that a best way for running the model is the following. If after running the model for one hour, no optimal solution has been reached, we stop the run at a 1% gap. In 95%

Table 8
Detailed schedule for September 2018.

Sequence type	Origin				Volume at demand points (cubic meter)			
	Product	Volume (cubic meter)	Injection start	Injection end	Chillan	Linares	San Fernando	Slop
s1	Die	6.000	01-09 0:00	02-09 5:16	1.462	739	3.787	12
	Ker	30	02-09 5:16	02-09 5:24	0	0	30	0
	G93	1.800	02-09 5:24	02-09 14:11	460	1.240	100	0
	G97	1.809	02-09 14:11	02-09 23:01	885	800	100	24
	G93	1.800	02-09 23:01	03-09 7:47	240	1.460	100	0
s3	G93	1.800	03-09 7:47	03-09 16:34	1.507	100	171	22
	C4	500	03-09 16:34	03-09 19:01	0	0	500	0
	C3	1.185	03-09 19:01	04-09 0:47	0	0	1.141	44
	C4	500	04-09 0:47	04-09 3:14	0	500	0	0
	G93	883	04-09 3:14	04-09 7:32	649	100	100	34
s6	G97	2.000	04-09 7:32	04-09 17:17	100	100	1.776	24
	Ker	30	04-09 17:17	04-09 17:26	0	0	30	0
	Die	8.000	04-09 17:26	06-09 8:28	5.070	2.830	100	0
	K Dom	1.541	06-09 8:28	06-09 15:59	699	0	842	0
	Ker	30	06-09 15:59	06-09 16:07	0	0	30	0
	G93	2.000	06-09 16:07	07-09 1:53	1.800	100	100	0
s3	G93	1.800	07-09 1:53	07-09 10:40	100	100	1.578	22
	C4	500	07-09 10:40	07-09 13:06	0	465	35	0
	C3	1.800	07-09 13:06	07-09 21:53	0	597	1.159	44
	C4	500	07-09 21:53	08-09 0:19	0	0	500	0
	G93	1.800	08-09 0:19	08-09 09:06	1.566	100	100	34
	Ker	30	08-09 09:06	08-09 9:15	0	0	30	0
s1	Die	7.347	08-09 9:15	09-09 21:05	3.663	100	3.571	13
	Ker	30	09-09 21:05	09-09 21:14	0	0	30	0
	G93	1.800	09-09 21:14	10-09 6:01	100	100	1.600	0
	G97	2.000	10-09 6:01	10-09 15:46	1.776	100	100	24
	G93	1.800	10-09 15:46	10-09 00:33	434	100	1.266	0
	Ker	30	10-09 00:33	10-09 00:41	0	0	30	0
s1	Die	6.000	11-09 0:41	12-09 5:58	4.439	100	1.449	12
	Ker	30	12-09 5:58	12-09 6:06	0	0	30	0
	G93	1.800	12-09 6:06	12-09 14:53	100	100	1.600	0
	G97	2.000	12-09 14:53	13-09 0:39	991	100	885	24
	G93	1.800	13-09 0:39	13-09 9:25	1.600	100	100	0
s2	G93	1.800	13-09 9:25	13-09 18:12	100	100	1.600	0
	C4	500	13-09 18:12	13-09 20:39	0	0	500	0
	G93	1.800	13-09 20:39	14-09 05:26	100	100	1.600	0
	Ker	30	14-09 05:26	14-09 05:34	0	0	30	0
s1	**Die**	**7.696**	**14-09 5:34**	**15-09 19:07**	**4.147**	**1.138**	**2.399**	**12**
	Ker	30	15-09 19:07	15-09 19:16	0	0	30	0
	G93	1.800	15-09 19:16	16-09 4:02	1.220	100	480	0
	G97	2.000	16-09 4:02	16-09 13:48	100	100	1.776	24
	G93	1.800	16-09 13:48	16-09 22:35	1.600	100	100	0
	Ker	30	16-09 22:35	16-09 22:43	0	0	30	0

of the instances, we obtain an optimal solution in less than 25 minutes.

8. Impact of the model and cost savings

The two main economic impacts brought by the model come from savings in reprocessing costs for the total slop volume and savings due to a better fulfillment of monthly contractual volumes, thus reducing contractual penalties. The overall economic impact of using the model, considering reduced fines and reprocessing costs, is approximately 10%. For confidentiality reasons is not possible to give further details in this matter.

8.1. Savings in reprocessing cost

Before using our model, on average ENAP used to collect 1500 cubic meters of slop per month (average data from 2013). After implementing our system, ENAP currently collects only around 750 cubic meters (average data from 2016), that is a reduction in the order of 50%. This is equivalent to 2% of total cost.

8.2. Savings in contractual penalties for ENAP

These penalties are associated with not fulfilling the contract with the client in Chillan. The use of the model yields an approximate annual reduction of 8% in fines as better scheduling allows a decrease in unfulfilled orders.

8.3. Quality of service to clients

It is important to note that the Chilean fuel market is open. About 50% of the national demand for diesel is being fulfilled by direct imports. Every client of ENAP has the option of importing refined products from foreign providers.

Thus, beside the direct fines to the client in Chillan, there is a critical issue of quality of service. Since that client has the option of importing the products directly from other distributors, not delivering in a timely fashion could lead to losing the client. Having a safety stock policy in San Fernando and Linares allows these distribution centers to provide a better quality of service to their own downstream clients. The impact of this improvement cannot be measured.

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

So far, we have considered that San Fernando was the last demand point on the pipeline, but there is also 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,

Table 9
Detailed schedule for September 2018.

Sequence type	Origin				Volume at demand points (cubic meter)			
	Product	Volume (cubic meter)	Injection start	Injection end	Chillan	Linares	San Fernando	Slop
s1	Die	6.000	16-09 22:43	18-09 3:59	2.899	994	2.095	12
	Ker	30	18-09 3:59	18-09 4:08	0	0	30	0
	G93	1.800	18-09 4:08	18-09 12:55	100	100	1.600	0
	G97	2.000	18-09 12:55	18-09 22:40	1.776	100	100	24
	G93	1.800	18-09 22:40	19-09 07:27	1.600	100	100	0
	Ker	30	19-09 07:27	19-09 7:36	0	0	30	0
s1	Die	17.220	19-09 7:36	22-09 19:36	7.902	4.265	5.040	13
	Ker	30	22-09 19:36	22-09 19:45	0	0	30	0
	G93	1.800	22-09 19:45	23-09 4:32	1.600	100	100	0
	G97	2.000	23-09 4:32	23-09 14:17	100	100	1.776	24
	G93	1.800	23-09 14:17	23-09 23:04	1.600	100	100	0
s2	G93	1.800	23-09 23:04	24-09 7:51	1.600	100	100	0
	C4	1.578	24-09 7:51	24-09 15:32	0	475	1.103	0
	G93	1.800	24-09 15:32	25-09 00:19	100	1.600	100	0
	Ker	30	25-09 00:19	25-09 0:28	0	0	30	0
s1	Die	15.491	25-09 0:28	28-09 4:02	6.521	100	8.858	12
	Ker	30	28-09 4:02	28-09 4:11	0	0	30	0
	G93	1.800	28-09 4:11	28-09 12:57	395	100	1.305	0
	G97	2.000	28-09 12:57	28-09 22:43	1.665	100	211	24
	G93	1.800	28-09 22:43	29-09 7:30	100	100	1.600	0
s6	G97	2.000	29-09 7:30	29-09 17:15	100	100	1.776	24
	Ker	30	29-09 17:15	29-09 17:24	0	0	30	0
	Die	6.467	29-09 17:24	01-10 0:56	3.633	2.734	100	0
	K Dom	688	01-10 0:56	01-10 4:18	314	0	374	0
	Ker	30	01-10 4:18	01-10 4:27	0	0	30	0
	G93	2.000	01-10 4:27	02-10 02:13	100	100	1.800	0

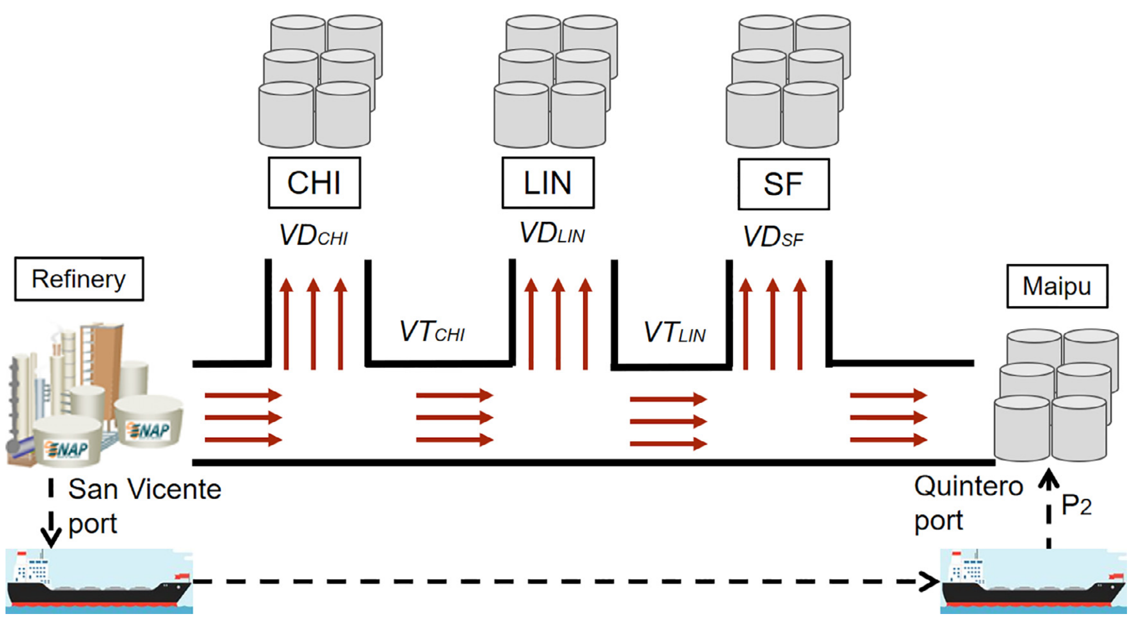

Fig. 8. Extended pipeline configuration.

(see Fig. 8), 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 possibilities:

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 and taken 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 was the one mostly used by ENAP. The present model, however, shows that using choice ii) could reduce the cost by 25%. Considering that the monthly demand of jet fuel in Maipu is about 20,000 cubic meters, this alterative gives ENAP a good savings opportunity.

Based of this finding, ENAP has used this option part of the time since 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.

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. Use of the system leads to savings in the order of 10% in the cost of operating the pipeline and also allows a better quality of service. One key aspect for achieving this success was the full cooperation and involvement of 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 attended the project meetings once a month and that is very rare in a company the size of ENAP.

This project has been a milestone for the company and was the kickoff of a new stage in the way they do planning, by switching from manual and empirical planning to an optimization model.

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