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Optimizing the monthly scheduling of crudes in a terminal-refinery system

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Abstract: This paper focuses on solving the optimization of crude oil operations scheduling carried out in a real system composed of a refinery and a marine terminal, over a monthly horizon. In the present article, we introduce a large-scale mixed-integer non-linear programming (MINLP) model that faithfully represents the operation and characteristics of the system. Considering the model's complexity and its non-linear and non-convex nature, the challenge lies in solving the model in a time frame that meets the user's needs. To tackle this problem, we develop a temporal decomposition method in conjunction with a linear approximation.

Keywords: Modelling and decision making in complex systems; Production planning and control; Continuous-time representation; Optimization and control of large-scale network systems; Temporal decomposition method.

1. INTRODUCTION

In this paper, we address the problem of crude oil operations scheduling carried out in a refinery with maritime access. It consists of a problem involving a complex system of ships, tanks, and crude distillation units, which it is difficult to solve.

In the literature, there is a great variety of works that tackle this issue, most of them using a discrete-time formulation approach (Assis et al. (2021); Hamisu et al. (2013); Saharidis and Ierapetritou (2009)) and a smaller number using a continuous-time formulation (Castro and Grossmann (2014); Cerdá et al. (2015)). However, there is a common point among these works, and it is that almost all of them solve the problem for a short scheduling horizon or apply to simplified refineries compared to the real ones. It can be said that few works address the monthly crude oil scheduling problem by using relatively detailed models, as in Zhang and Ricoux (2022).

Besides the classification concerning the time formulation, in crude oil scheduling problems, refineries can be classified according to the types of tanks involved. On the one hand, some refineries have two types of tanks: storage tanks and charging tanks. Storage tanks receive and store crude unloaded from ships, while charging tanks are used for the preparation of crude blends that feed the crude distillation units. On the other hand, there are refineries with only storage tanks. In these cases, crude blending is carried out in the storage tanks themselves or in the mixing pipelines. It should be noted that most papers focus on refineries of the first type (Furman et al. (2007); Hamisu et al. (2013); Jia et al. (2003)) and, therefore, there are not many articles dealing with refineries of the second type (Cerdá et al. (2015); Saharidis and Ierapetritou (2009)).

Tanks can also be classified according to the types of crude oil stored. However, it is unusual to find articles that cover this characteristic. Where it is included, a small number of classes are usually considered and tanks have a permanent grade associated with them.

An important point to take into account when formulating a model is that there is a trade-off between model complexity and resolution time. Simple models allow us to obtain solutions in a short time, but they are hardly applicable in reality. On the other hand, complex models give detailed solutions but take a long time to achieve them, so we cannot respond within the time demanded by the process itself. Thus, the difficulty lies in formulating a model that faithfully represents the process and provides us with solutions applicable to the real operation but that, simultaneously, can be solved in a time frame that meets the user's needs.

Through this article, we seek to contribute to the area of crude oil operations scheduling optimization from two points of view. First, we develop a mixed-integer non-linear programming (MINLP) model based on continuous-time formulation, which represents the operation and characteristics of a terminal-refinery system, corresponding to a real case. This refinery has exclusively storage tanks, which can adopt up to eight different classes. The grades are not

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predetermined for each tank, so the same tank can change class over the horizon.

Second, due to the complexity of the model, and its non-linear and non-convex nature, it is impossible to solve it monolithically for long scheduling horizons. Therefore, we develop a temporal decomposition technique in conjunction with a linear approximation (i.e., we obtain a MILP model), which allows us to solve the scheduling for a monthly horizon in a shorter time span.

The rest of the paper is structured as follows. The description of the system is given in Section 2. In Section 3, we explain certain characteristics of how the refinery works, which are of great relevance at the time of developing the model. The proposed mathematical formulation is described in Section 4. The proposed solution (decomposition strategy and linear approximation) for the MINLP model is described in Section 5. Next, a problem instance and computational results are reported in Section 6. Finally, conclusions are drawn in Section 7.

2. SYSTEM DESCRIPTION

Figure 1 shows the configuration of the refinery under study. There is a terminal where vessels arrive to unload the crude oil. Also, there is a pipeline that connects the terminal and the tank farm. The tank farm consists only of storage tanks but, within it, it is possible to distinguish two types of tanks, called discharge tanks and refinery tanks. The difference between both types is that the discharge tanks cannot feed the crude distillation units (CDUs) since they are not physically connected to them, so they can only store crudes and transfer them to the refinery tanks. The discharge tanks are located halfway between the port and the refinery tank area. Finally, there are the CDUs that process the crude blends to meet the demand for final products. In this case study, there are two CDUs.

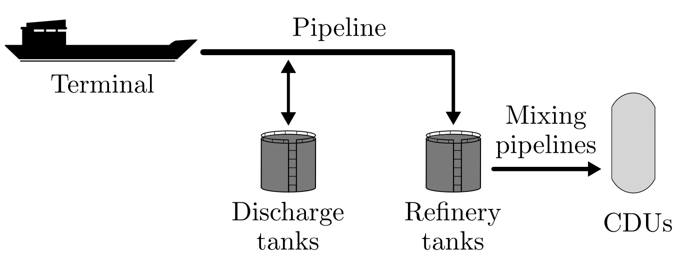

Fig. 1. Schematic of system

3. REFINERY CHARACTERISTICS

3.1 Tank and crude oil classification

There are seven grades to classify both tanks and crude oils: T1, T2, T3, T4, T5, T6, T7.

The classification of tanks is based on rules that evaluate their composition (i.e., types and volumes of crude oil). Each tank has only one grade associated with it at a time, but it may vary over the horizon.

A key point related to crudes is their unloading from ships since the grade of the receiving tanks must be taken into account. Crude oil can be unloaded into tanks of different classes, but there is a priority scale that relates crude oil grades to receiving tank grades.

3.2 Crude oil distillation units and processes

Three types of crude processes are carried out in the refinery (i.e. standard, asphaltic, and low-sulfur fuel oil) and for each of them, there are recipes that indicate the grades and proportions of tanks allowed in the preparation of the feed blends.

Concerning the asphaltic process, it is important to mention that only one campaign is carried out during the month, whose start and end dates are known at the beginning of the horizon and must be taken into account at the time of solving the scheduling. For the rest of the processes, the campaign dates are not fixed and are obtained as a result of the optimization.

An important point in feeding CDUs is that we should avoid frequent changeovers, as they result in inefficient operation. Therefore, once a feed mixture is formed, a minimum time of unchanged operation in the participating tanks must be met.

As previously mentioned, the refinery has two crude distillation units. However, these CDUs are not identical. In CDU 1, it is possible to carry out standard or asphaltic processes but not low-sulfur fuel oil campaigns. On the other hand, in CDU 2, it is possible to carry out standard or low-sulfur fuel oil processes, but asphaltic campaigns are not allowed.

4. MODEL FORMULATION

4.1 Model assumptions

- There is only one pipeline connecting the terminal with the refinery, and only one vessel can unload at a time.
- A vessel that has started unloading crude can leave the terminal once it is completely emptied.
- Unloading of vessels and discharge tanks cannot be carried out simultaneously as both use the same pipeline.
- Each vessel carries a single type of crude oil and it is considered that the pipeline has a negligible volume compared to the volume to be unloaded.
- A tank cannot receive crude from a vessel and feed a CDU at the same time. After receiving crude, a tank should stay idle during some time for brine settling and removal before feeding some CDU.
- A new grade, "undefined" (TUND), is established to represent the status of tanks when they do not meet any of the classification rules.
- A perfect mixing of the crudes supplied to a CDU from different tanks occurs in the mixing pipelines.
- It is not allowed to stop feeding the CDUs.

4.2 Notation

Sets

- B = vessels
- BC = vessel-crude pairs
- C = crude oils
- CL = tank and crude grades
- CLC = crude-grade pairs
- K = key components

- M = recipes
- MCL = classes allowed in each recipe
- P = processes
- PM = recipes allowed in each process
- $Q = QL \cup QR$. All tanks
- QL = discharge tanks
- QR = refinery tanks
- S = time slots
- U = crude distillation units
- UM = recipes allowed in each CDU

Parameters

- AT_b = arrival time of vessel
- $CDMG_b$ = demurrage or sea waiting cost
- $CFRAC_{m,cl,u,s}$ = cost due to non-compliance with the minimum proportion of each grade in the recipe
- $\underline{CK}_{k,u,s}$ = cost related to violation of lower boundary of key component concentration
- $\overline{CK}_{k,u,s}$ = cost related to violation of upper boundary of key component concentration
- $COP_{u,p}$ = cost due to overproduction
- $CSP_{u,p}$ = cost due to underproduction
- $CTDN_b$ = departure tardiness cost
- $DEMP_{u,p}$ = demand of process for CDU
- EDT_b = departure time of vessel
- $ETAC$ = end-time of asphaltic processing campaign
- $\underline{FPU}_{u,p}$ = minimum rate of process in CDU
- $\overline{FPU}_{u,p}$ = maximum rate of process in CDU
- $FRAC_{m,cl}$ = minimum proportion of each grade allowed in the recipe
- H = end-time of the scheduling horizon
- $PR_{c,k}$ = volumetric concentration of a key component in a crude
- $PRI_{c,cl}$ = priority of unloading crude oil c in a tank of grade cl
- $\underline{PROP}_{u,k}$ = minimum allowed concentration of key component in the feed
- $\overline{PROP}_{u,k}$ = maximum allowed concentration of key component in the feed
- $\overline{UND}$ = maximum proportion of tanks with grade "undefined" allowed in recipes

Variables

- dmg_b = demurrage of vessel b
- $dmgs_{b,s}$ = auxiliary variable to calculate dmg_b
- ds_s = length of slot s
- $fcbq_{c,b,q,s}$ = amount of crude c transferred from b to q during s
- $fcbqcl_{c,b,q,s,cl}$ = amount of crude c transferred from vessel b to tank q with grade cl during slot s
- $fcl_{cl,qr,u,s}$ = amount of crude mix transferred from tank qr with grade cl to CDU u during slot s
- $fcqq_{c,ql,qr,s}$ = amount of crude c transferred from ql to qr during s
- $fcqu_{c,qr,u,s}$ = amount of crude c transferred from qr to u during s
- $fmu_{m,u,s}$ = m recipe volume processed by CDU u during slot s
- $fqq_{ql,qr,s}$ = amount of crude mix transferred from ql to qr during s
- $fqu_{qr,u,s}$ = amount of crude mix transferred from qr to u during s
- $fu_{u,s}$ = total amount of crude mix transferred to u during s
- $i_{q,s}$ = total level in q at the beginning of s
- $ic_{q,c,s}$ = amount of c in q at the beginning of s
- is_s = start-time of slot s
- $klwr_{k,u,s}$ = violation of lower boundary of key component concentration
- $kupr_{k,u,s}$ = violation of upper boundary of key component concentration
- $opm_{u,p}$ = overproduction concerning the demand of p by u
- $spm_{u,p}$ = underproduction concerning the demand of p by u
- $subfrac_{m,cl,u,s}$ = level of non-compliance with the minimum proportion of each grade in the recipe
- tdn_b = departure tardiness of vessel b
- $tdns_{b,s}$ = auxiliary variable to calculate tdn_b
- ts_s = end-time of slot s
- z = cost function

Binary variables

- $tq_{cl,q,s}$ = indicates the grade of each tank
- $xb_{b,s}$ = is equal to 1 if vessel b remains docked during s; 0 otherwise
- $xfd_{b,s}$ = is equal to 1 if vessel b undocks at the end of s; 0 otherwise
- $xid_{b,s}$ = is equal to 1 if vessel b docks at the beginning of s; 0 otherwise
- $xmu_{m,u,s}$ = is equal to 1 if the recipe m is selected to feed the CDU u

4.3 Constraints

To calculate the difference between processed volume and required demand of each process in each CDU, we use (1) and (2).

$$opm_{u,p} \;\geq\; \sum_{s} \sum_{m \in PM \cap UM} fmu_{m,u,s} \;-\; DEMP_{u,p} \qquad \forall u \in U,\ \forall p \in P \tag{1}$$

$$spm_{u,p} \;\geq\; DEMP_{u,p} \;-\; \sum_{s} \sum_{m \in PM \cap UM} fmu_{m,u,s} \qquad \forall u \in U,\ \forall p \in P \tag{2}$$

Each CDU is fed with only one recipe at a time.

$$\sum_{m \in UM} xmu_{m,u,s} = 1 \quad \forall u \in U, \forall s \in S \tag{3}$$

The volume of the mixture is equal to the total feed volume (4). For all other recipes not selected, it is zero (5). Here, we apply the big-M method explained by Winston (2004).

$$\sum_{m \in UM} fmu_{m,u,s} = fu_{u,s} \quad \forall u \in U, \forall s \in S \tag{4}$$

$$fmu_{m,u,s} \;\leq\; M1 * xmu_{m,u,s} \forall (u,m) \in UM,\ \forall s \in S \tag{5}$$

Each tank belongs to only one grade (6).

$$\sum_{cl} tq_{cl,q,s} = 1 \quad \forall q \in Q, \forall s \in S \tag{6}$$

To calculate the volume that each CDU receives from each tank belonging to a certain grade, we use (7) and (8).

$$\sum_{cl} fcl_{cl,qr,u,s} \;=\; fqu_{qr,u,s} \qquad \forall qr \in QR,\ \forall u \in U,\ \forall s \in S \tag{7}$$

$$fcl_{cl,qr,u,s} \leq M1 * tq_{cl,qr,s} \quad \forall cl \in CL,\ \forall qr \in QR,\ \forall u \in U,\ \forall s \in S \tag{8}$$

For each recipe, a minimum proportion of each permitted grade is established, although it is not imperative (9). For the rest of the grades, the volume must be null (10).

$$\sum_{qr} fcl_{cl,qr,u,s} \geq FRAC_{m,cl} * fu_{u,s} - M1 * (1 - xmu_{m,u,s}) - subfrac_{m,cl,u,s} \quad \forall (m,cl) \in MCL,\ \forall (u,m) \in UM,\ \forall s \in S \tag{9}$$

$$\sum_{qr} fcl_{cl,qr,u,s} \leq M1 * (1 - xmu_{m,u,s}) \quad \forall (m,cl) \notin MCL, \forall (u,m) \in UM, \forall s \in S \tag{10}$$

Equation (11) indicates the maximum proportion of tanks with grade "undefined" allowed in the recipes.

$$\sum_{qr} fcl_{cl,qr,u,s} \leq \overline{UND} * fu_{u,s} \quad cl = TUND, \forall u \in U, \forall s \in S \tag{11}$$

Start and end dates of the asphaltic processing campaign.

$$is_s \geq STAC * xmu_{m,u,s} \quad p = Asph, \forall (u,m) \in UM, \forall (p,m) \in PM, \forall s \in S \tag{12}$$

$$ts_s \leq ETAC + M2 * (1 - xmu_{m,u,s}) \quad p = Asph, \forall (u,m) \in UM, \forall (p,m) \in PM, \forall s \in S \tag{13}$$

Calculation of volumes of mixtures, considering the boundaries in the flow rates of each process in each CDU.

$$\sum_{m \in UM \cap PM} fmu_{m,u,s} \leq \overline{FPU}_{u,p} * ds_s \quad \forall u \in U, \forall p \in P, \forall s \in S \tag{14}$$

$$\sum_{mbis \in UM \cap PM} fmu_{mbis,u,s} \geq \underline{FPU}_{u,p} * ds_s - M1 * (1 - xmu_{m,u,s}) \quad \forall (u,m) \in UM, \forall (p,m) \in PM, \forall s \in S \tag{15}$$

Using (16) and (17), we calculate the volume of crude oil unloaded from a vessel in a tank whose grade is *cl*.

$$\sum_{cl} fcbqcl_{c,b,q,s,cl} = fcbq_{c,b,q,s} \quad \forall (b,c) \in BC, \forall q \in Q, \forall s \in S \tag{16}$$

$$fcbqcl_{c,b,q,s,cl} \leq M3 * tq_{cl,q,s} \quad \forall (b,c) \in BC, \forall q \in Q, \forall s \in S, \forall cl \in CL \tag{17}$$

The concentration of key components in the feedstock for the CDUs is given by (18)-(19).

$$\sum_{qr} \sum_{c} fcqu_{c,qr,u,s} * PR_{c,k} \leq \overline{PROP}_{u,k} * fu_{u,s} + kupr_{k,u,s} \quad \forall k \in K,\ \forall u \in U,\ \forall s \in S \tag{18}$$

$$\sum_{qr} \sum_{c} fcqu_{c,qr,u,s} * PR_{c,k} \geq \underline{PROP}_{u,k} * fu_{u,s} - klwr_{k,u,s} \quad \forall k \in K,\ \forall u \in U,\ \forall s \in S \tag{19}$$

The discharge of crude oil from vessel b cannot start before its arrival time.

$$is_s \geq AT_b * xid_{b,s} \quad \forall b \in B,\ \forall s \in S \tag{20}$$

The demurrage is calculated as the time elapsed between the arrival of a ship and the start of its unloading.

$$dmgs_{b,s} \geq is_s - AT_b * xid_{b,s} - H * (1 - xid_{b,s}) \quad \forall b \in B,\ \forall s \in S \tag{21}$$

$$dmg_b \geq \sum_{s} dmgs_{b,s} \quad \forall b \in B \tag{22}$$

If vessel b leaves the terminal after its expected departure time EDT_b, it should pay a penalty that will be proportional to the departure tardiness tdn_b. The value of the mentioned variable is defined by (23)-(24).

$$tdns_{b,s} \geq ts_s - EDT_b - H * (1 - xb_{b,s}) \quad \forall b \in B,\ \forall s \in S \tag{23}$$

$$tdn_b \geq tdns_{b,s} \quad \forall b \in B,\ \forall s \in S \tag{24}$$

The crude oil concentration at the outlet of a tank must be the same as the one inside the tank. This principle is satisfied by (25) and (26). Note that each of these equations yields two bilinear terms that are non-convex.

$$i_{qr,s} * fcqu_{c,qr,u,s} = ic_{qr,c,s} * fqu_{qr,u,s} \quad \forall c \in C,\ \forall qr \in QR,\ \forall u \in U,\ \forall s \in S \tag{25}$$

$$i_{ql,s} * fcqq_{c,ql,qr,s} = ic_{ql,c,s} * fqq_{ql,qr,s} \quad \forall c \in C,\ \forall ql \in QL,\ \forall qr \in QR,\ \forall s \in S \tag{26}$$

The rule formulation that determines whether the tank classifies as T2 is shown. A tank is considered T2 class if it contains at least 65% T2 crude oil. The rest of the rules are formulated similarly.

$$\sum_{c \in CLC} ic_{q,c,s} - 0.65 * i_{q,s} \leq M4_q * tq_{cl,q,s} \quad cl = T2,\ \forall q \in Q,\ \forall s \in S \tag{27}$$

$$\sum_{c \in CLC} ic_{q,c,s} - 0.65 * i_{q,s} \geq M4_q * (tq_{cl,q,s} - 1) \quad cl = T2,\ \forall q \in Q,\ \forall s \in S \tag{28}$$

4.4 Objective function

The objective function is given by (29). The first term represents the costs due to the difference between processed volume and required demand. The second term refers to demurrage and departure tardiness costs. The third term involves the cost of not meeting the minimum proportions of each grade in each recipe. The fourth term represents the cost of violating the established limits for the concentration of key components in feed mixtures. The fifth term maximizes the unloading of crude oil into priority tanks according to their grades.

$$\begin{aligned} MIN\ z = & \sum_{u} \sum_{p} (COP_{u,p} * opm_{u,p} + CSP_{u,p} * spm_{u,p}) \\ & + \sum_{b} (CDMG_b * dmg_b + CTDN_b * tdn_b) \\ & + \sum_{m \in MCL \cap UM} \sum_{cl} \sum_{u} \sum_{s} (CFRAC_{m,cl,u,s} * subfrac_{m,cl,u,s}) \\ & + \sum_{k} \sum_{u} \sum_{s} (\underline{CK}_{k,u,s} * klwr_{k,u,s} + \overline{CK}_{k,u,s} * kupr_{k,u,s}) \\ & - \sum_{c \in BC} \sum_{b} \sum_{q} \sum_{s} \sum_{cl} (PRI_{c,cl} * fcbqcl_{c,b,q,s,cl}) \end{aligned} \tag{29}$$

5. PROPOSED SOLUTION METHOD

Initially, the formulated model works correctly for short scheduling horizons but, as mentioned above, the horizon with which the refinery works is 30 days, and it is impossible to solve it in a monolithic way. Therefore, we present below the method developed. Although it does not guarantee a global optimum, it allows us to obtain feasible and good-quality solutions in a sensible time and for a one-month scheduling horizon.

First, constraints (25) and (26) are replaced by pairs (30)-(31) and (32)-(33), respectively, and from them, we approximate the outgoing volume of a given crude oil from a tank. The parameter $AVCONC$ represents an average value of the crude oil concentration in the tank and is updated at each iteration. The parameter DEV is a user-defined deviation to achieve convergence over iterations.

$$fcqu_{c,qr,u,s} \leq (AVCONC_{c,qr,s} + DEV_{c,qr,s}) * fqu_{qr,u,s} \quad \forall c \in C, \forall qr \in QR, \forall u \in U, \forall s \in S \tag{30}$$

$$fcqu_{c,qr,u,s} \geq (AVCONC_{c,qr,s} - DEV_{c,qr,s}) * fqu_{qr,u,s} \quad \forall c \in C, \forall qr \in QR, \forall u \in U, \forall s \in S \tag{31}$$

$$fcqq_{c,ql,qr,s} \leq (AVCONC_{c,ql,s} + DEV_{c,ql,s}) * fqq_{ql,qr,s} \quad \forall c \in C, \forall ql \in QL, \forall qr \in QR, \forall s \in S \tag{32}$$

$$fcqq_{c,ql,qr,s} \geq (AVCONC_{c,ql,s} - DEV_{c,ql,s}) * fqq_{ql,qr,s} \quad \forall c \in C, \forall ql \in QL, \forall qr \in QR, \forall s \in S \tag{33}$$

Second, what we do in this method is to solve the horizon gradually, for which we iterate over the scheduled vessels respecting the order of arrival. In each iteration, we incorporate a vessel, and each of them defines a sub-horizon to be optimized. From the obtained solution, we fix a set of variables. Then, the unfixed variables are successively re-optimized in subsequent iterations. We repeat the procedure until we solve the last ship and, thus, obtain the complete horizon schedule. We present the steps in more detail below:

(1) Select the vessel (sub-horizon) to be optimized, following the scheduled order of arrival.
(2) Set the start of the sub-horizon, which is equal to the departure date of the previous ship. If it is the first ship, then it is equal to the beginning of the horizon.
(3) Set the expected end date of the current sub-horizon.
(4) Calculate the volume demanded for each process in each CDU.
(5) Assign slots to the sub-horizon.
(6) For the slots assigned to the sub-horizon of the current iteration, set the concentration values in the tanks equal to the values obtained at the end of the previous sub-horizon. If it is the first sub-horizon, the values are equal to the initial concentrations.
(7) For the slots assigned to the previous sub-horizons:
    - Calculate the concentration values (for each tank and slot) obtained from the last solution.
    - Calculate an average value (for each tank and slot) considering the concentrations obtained in all previous iterations.
(8) Solve the model, and from the obtained solution:
    - Set the end of the sub-horizon equal to the ship's departure date.
    - Set the values of the following variables:
        - ◦ Start time, end time, and length of slots.
        - ◦ Binary variables of ship unloading.
        - ◦ Demurrage and departure tardiness values.
        - ◦ Binary variables of tank loading and unloading.
(9) Repeat the procedure until all ships are covered.

6. RESULTS

In order to check the effectiveness of the proposed method, a real case study is carried out. It consists of a refinery with 11 tanks (eight refinery tanks, three discharge tanks), two CDUs, and two key properties. In addition, the arrival of 11 ships is considered. A solution with relative gap less than 5% has been found for this problem (11 187 binary variables, 395 098 real ones, and 685 827 constraints) in about 17 min using GAMS with GUROBI 9.5.2 over an Intel Core i7-10510U 2.30 GHz CPU machine with 16GB of RAM.

Figure 2 shows the Gantt chart for the ships. We can observe that the vessels incurring demurrage are numbers 3, 4, 9, and 11. In the last two, the delay is caused by waiting for the previous ship to finish unloading.

On the other hand, Figure 3 displays the grade of each tank in each slot of the scheduling horizon. We can notice, in this case, that none of them kept the same class throughout the month and that no tank adopted the grade T7.

7. CONCLUSION

As mentioned above, based on the method presented, it is possible to solve the monthly scheduling problem of a real case in a relatively short time and for a complex model.

Also, we can observe that the duration values vary greatly between slots, this is because the state changes of the tanks are not regular. Therefore, if a discrete-time approach were used, the ability to respond to changes occurring very close in time could be lost if a large number of slots are not used, but this would considerably increase the size of the model and the computational effort required.

Finally, from Figure 3, the importance of not fixing grades to tanks is reflected since it reduces the flexibility of the solution, and it could even be the case that a tank becomes idle because there are no crudes available that match its class. It is also important to consider the grade "undefined" because it serves as a transition between classes to avoid infeasibilities.

Future works include extending the model to incorporate downstream processing units and adapting the model to a two-stage stochastic programming approach.

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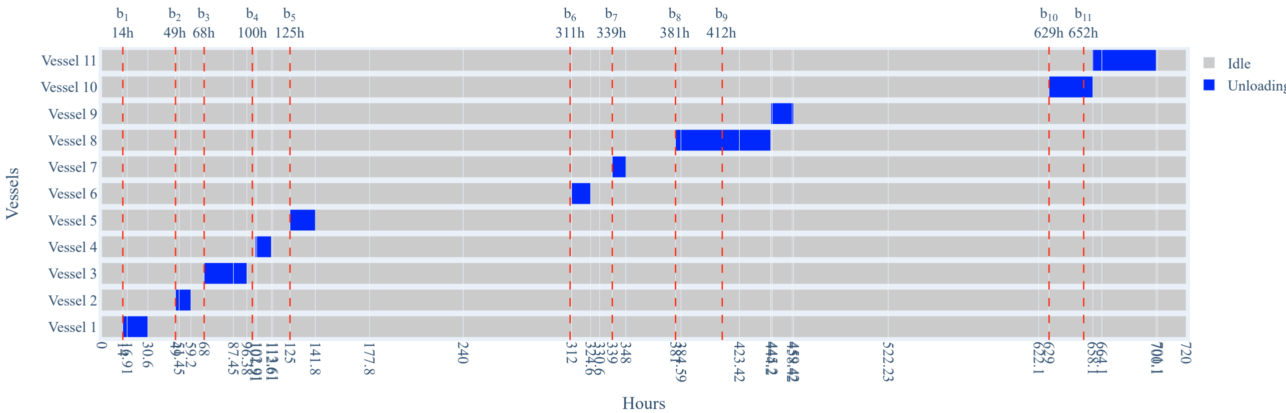

Fig. 2. Gantt chart for vessels

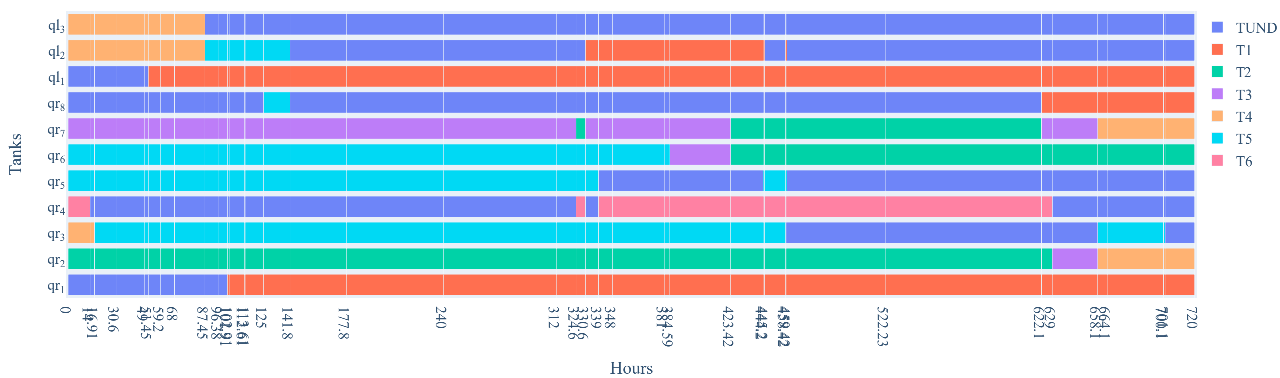

Fig. 3. Evolution of tank grades

REFERENCES

Assis, L.S., Camponogara, E., and Grossmann, I.E. (2021). A milp-based clustering strategy for integrating the operational management of crude oil supply. *Computers and Chemical Engineering*, 145. doi:10.1016/j.compchemeng.2020.107161.

Castro, P.M. and Grossmann, I.E. (2014). Global optimal scheduling of crude oil blending operations with rtn continuous-time and multiparametric disaggregation. *Industrial and Engineering Chemistry Research*, 53, 15127–15145. doi:10.1021/ie503002k.

Cerdá, J., Pautasso, P.C., and Cafaro, D.C. (2015). Efficient approach for scheduling crude oil operations in marine- access refineries. *Industrial and Engineering Chemistry Research*, 54, 8219–8238. doi:10.1021/acs.iecr.5b01461.

Furman, K.C., Jia, Z., and Ierapetritou, M.G. (2007). A robust event-based continuous time formulation for tank transfer scheduling. volume 46. doi:10.1021/ie061516f.

Hamisu, A.A., Kabantiok, S., and Wang, M. (2013). Refinery scheduling of crude oil unloading with tank inventory management. *Computers and Chemical Engineering*, 55, 134–147. doi:10.1016/j.compchemeng.2013.04.003.

Jia, Z., Ierapetritou, M., and Kelly, J.D. (2003). Refinery short-term scheduling using continuous time formulation: Crude-oil operations. *Industrial and Engineering Chemistry Research*, 42. doi:10.1021/ie020124f.

Saharidis, G.K. and Ierapetritou, M.G. (2009). Scheduling of loading and unloading of crude oil in a refinery with optimal mixture preparation. *Industrial and Engineering Chemistry Research*, 48, 2624–2633. doi:10.1021/ie801155w.

Winston, W.L. (2004). *Operations Research: Applications and Algorithms, Forth Edition.*

Zhang, C. and Ricoux, P. (2022). Monthly schedule of crude refinery: Multi-scale strategy and multi-criteria objective. *Computers and Chemical Engineering*, 164. doi:10.1016/j.compchemeng.2022.107866.