Minimizing risk in the scheduling of crudes in an oil refinery

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Abstract: This paper focuses on formulating and solving the optimization of crude oil operations scheduling carried out in a system composed of a refinery and a marine terminal. The main challenge lies in coordinating the decisions made at both facilities and, at the same time, dealing with the uncertainties inherent in this activity. To tackle this problem, we present a continuous-time mixed-integer non-linear programming (MINLP) formulation. Furthermore, uncertainty in the ship arrival times is considered through a two-stage stochastic programming approach. Finally, the Conditional Value-at-Risk (CVaR) risk measure is employed to weigh the risk of having high costs relative to the worst scenarios. In this way, the proposed model is capable of supporting the decision-making process under uncertainty in an integral way.

Keywords: Stochastic optimization; Continuous-time representation; Crude oil scheduling; Uncertain oil supply; Conditional Value-at-Risk.

1. INTRODUCTION

The optimization of crude oil operations scheduling in refineries with marine access is a complex problem that involves: the allocation of ships to tanks and tanks to crude distillation units (CDUs), the calculation of crude oil volumes transferred between resources, and the calculation of the composition of the mixtures.

A wide variety of papers addressed this problem (Furman et al., 2007; Jia et al., 2003; and Lee et al., 1996). These studies assumed refineries with separate storage and charging tanks. The storage tanks are used for receiving and storing the crude from the ships and the charging tanks are used for blending the crudes and feeding the CDUs.

A smaller number of works have been focused on oil refineries without charging tanks. In this kind of refineries, the blending process takes place in storage tanks or in pipelines that feed CDUs. Some of the most relevant works are Cerdá et al. (2015), Pinto et al. (2000), and Reddy et al. (2004).

All the works mentioned above tackled the problem through a deterministic approach. However, stochastic programming models have also been developed to address the crude oil scheduling problem under uncertainty.

In Wang and Rong (2010), a two-stage robust model was proposed to address the crude oil scheduling problem considering uncertainty in vessel arrival times and product demand. Cao et al. (2010) developed a stochastic chance-constrained MINLP model to solve the crude oil scheduling problem under demand uncertainty. Oliveira et al. (2016) proposed a two-stage stochastic MILP model that defines the scheduling of oil pumping through a pipeline and the sequencing of ships berthing at a terminal. It should be noted that these authors reported a model based on discrete-time formulation.

In this paper, we develop a two-stage stochastic MINLP model based on continuous-time representation, considering uncertainty in vessel arrival times, to tackle the scheduling problem of crude oil operations in a marine-access refinery. Additionally, we extend the proposed model by incorporating the Conditional Value-at-Risk (CVaR) risk measure in the objective function. To the best of our knowledge, no other paper considers at once a two-stage stochastic approach, CVaR and continuous-time formulation applied to the optimization of crude oil operations scheduling.

The rest of the paper is structured as follows. The problem definition is given in Section 2. The proposed mathematical formulation is described in Section 3. The risk problem and its management method are presented in Section 4. The proposed solution for the MINLP problem is described in Section 5. Next, problem instances and computational results are reported in Section 6. Finally, conclusions are drawn in Section 7.

2. PROBLEM DESCRIPTION

Often, crude oil is supplied to a refinery through vessels that arrive at a marine terminal close to it. This terminal-refinery system is connected by an oil pipeline.

Figure 1 gives a schematic of the crude oil operations in a typical marine-access refinery. Furthermore, the operations involve the unloading of crudes into multiple storage tanks from the ships arriving at different times, the blending of crudes in mixing pipelines, and the feed of CDUs performed by storage tanks at different rates over time.
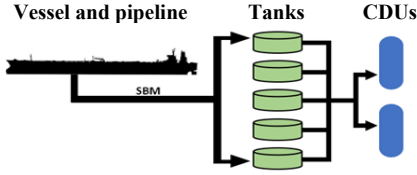
Figure 1. Schematic of crude oil operations.

The integration of this system implies a challenge due to the need to coordinate the decisions made at the terminal and the refinery, each one with different objectives. While the former is interested in unloading the ships as soon as possible to avoid demurrage and departure tardiness costs, the latter is concerned with receiving what it exactly needs for the planned production.

Therefore, uncertainties are inherent in the overall process due to the dependence between crude oil supply and marine weather. The latter affects the arrival time of vessels and, thus, the start of offloading activities and downstream decisions. To tackle this problem, we propose a model based on two-stage stochastic programming with recourse (Birge and François Louveaux, 2011). Essentially, two-stage stochastic programming models involve two types of decision variables: first-stage variables (here-and-now variables) which have to be implemented now and influence all future decisions, and second-stage ones that will be implemented later on when more information about the process may be available (recourse variables, wait-and-see).

In this paper, the first-stage decisions refer to the variables related to the supply of crude blends to CDUs, that is, allocation of tanks and total volumes transferred. The start-time, end-time, and length of slots are also first-stage decisions. Regarding the second stage decisions, they include the variables related to the activities carried out in the marine terminal, the inventory level in tanks, and the composition of mixtures delivered, that is, the amount of each type of crude transferred from tanks to CDUs. Furthermore, the crude oil supply availability is subject to uncertainty which is represented by a discrete set of scenarios that contemplates different arrival times.

Available data to solve the problem include: set of scenarios with their respective probabilities, the arrival time of the vessels in each scenario, volume and type of crude oil transported; limits on flow rates between resources; the number of tanks, their capacities, and initial inventory; the CDU data, such as the feed quality specifications; economic data including costs due to vessel demurrage and departure tardiness, costs because of differences between processed volume and required demand; lastly, CDU demands.

3. MODEL FORMULATION

In this section, we introduce the two-stage stochastic MINLP model. It is important to note that the precedence between vessels is not subject to the order of the elements in the set of vessels, as stated in Cerdá et al. (2015), and there is no pre-allocation of time slots for each vessel as in Reddy et al. (2004). In the present work, predefined precedence has been applied where the set of slots is pre-ordered and the

optimization algorithm allocates each vessel to some of these slots; Gómez Palacín et al. (2019) and Gómez Palacín (2020).

Also, it is relevant to highlight the following characteristics. The scheduling horizon is divided into variable-length slots s, synchronized across all tanks. Three mutually exclusive states are defined for the tanks: loading, unloading, and idle. Then, a new slot is activated whenever a tank changes its state. Even so, a tank can maintain its state during consecutive time slots.

3.1 Model assumptions

The proposed MNILP formulation is based on the following assumptions:
1) There is an SBM pipeline connecting the terminal with the refinery, so only one vessel can unload at any moment.
2) A vessel that has started unloading crude can leave the terminal once it is completely emptied.
3) 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.
4) 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.
5) A maximum of two tanks can be loaded simultaneously and transfers between tanks are not allowed.
6) A tank can at most feed two CDUs simultaneously.
7) At most three tanks are allowed to concurrently feed a CDU and time to changeover tanks is negligible.
8) A perfect mixing of crudes occurs in the pipelines.
9) It is not allowed to stop feeding the crude distillation units.

3.2 Notation

Sets
- S = time slots
- B = vessels
- Q = tanks
- U = crude distillation units
- C = types of crude oils
- K = key components
- E = scenarios

Parameters
- H = length of the scheduling horizon
- $\overline{FQ_q}$ = maximum rate of crude transfer to tank q
- FQ_q = minimum rate of crude transfer to tank q
- $\overline{FB_b}$ = maximum rate of crude transfer from vessel b
- $\underline{FB_b}$ = minimum rate of crude transfer from vessel b
- $\overline{OFQ_q}$ = maximum rate of crude transfer from tank q
- OFQ_q = minimum rate of crude transfer from tank q
- $\overline{FU_u}$ = maximum rate of crude transfer to CDU u
- $\underline{FU_u}$ = minimum rate of crude transfer to CDU u
- $PR_{c,k}$ = volumetric concentration of the key component k in the crude type c
- $\overline{PROP_{u,k}}$ = maximum allowed concentration of key component k in the feedstock of CDU u
- $\underline{PROP_{u,k}}$ = minimum allowed concentration of key component k in the feedstock of CDU u
- ST = time to settle and remove the brine
- dem_u = total demand of blended crude for CDU u

- COP_u = cost due to positive difference between processed volume and required demand by u
- CSP_u = cost due to negative difference between processed volume and required demand by u
- $AT_{b,e}$ = arrival time of vessel b under scenario e
- $EDT_{b,e}$ = departure time of vessel b under scenario e
- $CDMG_b$ = demurrage or sea waiting cost
- $CTDN_b$ = departure tardiness cost
- $Vol_{b,c}$ = amount of crude c in the vessel b
- $IIC_{q,c}$ = initial amount of crude c in the tank q
- $CONC_{q,c}$ = initial crude c concentration in the tank q
- α = confidence level
- λ = trade-off coefficient
- π_e = scenario e probability

Variables
- ts_s = end-time of slot s
- is_s = start-time of slot s
- ds_s = length of slot s
- $fcbq_{c,b,q,s,e}$ = amount of crude c transferred from b to q during s
- $fbq_{b,q,s,e}$ = amount of crude transferred from b to q during s
- $fcb_{c,b,s,e}$ = total amount of crude c unloaded from b during s
- $fqu_{q,u,s}$ = amount of crude mix transferred from q to u during s
- $fcqu_{c,q,u,s,e}$ = amount of crude c transferred from q to u during s under scenario e
- $fu_{u,s}$ = total amount of crude mix transferred to u during s
- $ic_{q,c,s,e}$ = amount of c in q at the beginning of s
- $i_{q,s,e}$ = crude level in q at the beginning of s
- $ie_{q,s,e}$ = crude level in q at the end of the scheduling horizon
- $ice_{q,c,s,e}$ = amount of c in q at the end of the horizon
- op_u = positive difference between processed volume and required demand by u
- sp_u = negative difference between processed volume and required demand by u
- $dmg_{b,e}$ = demurrage of vessel b under scenario e
- $dmgs_{b,s,e}$ = auxiliary variable to calculate $dmg_{b,e}$
- $dep_{b,s,e}$ = departure time of vessel b under scenario e
- $tdn_{b,e}$ = departure tardiness of vessel b under scenario e
- $tdns_{b,s,e}$ = auxiliary variable to calculate $tdn_{b,e}$
- ze_e = cost associated with scenario e
- var = Value-at-Risk
- $cvar$ = Conditional Value-at-Risk
- ϕ_e = auxiliary variable to assess the CVaR

Binary variables
- $xb_{b,s,e}$ = is equal to 1 if vessel b remains docked during s under scenario e; 0 otherwise
- $xid_{b,s,e}$ = is equal to 1 if vessel b docks at the beginning of s under scenario e; 0 otherwise
- $xfd_{b,s,e}$ = is equal to 1 if vessel b undocks at the end of s under scenario e; 0 otherwise
- $xq_{q,s,e}$ = is equal to 1 if tank q is receiving crude during s under scenario e
- $y_{q,u,s}$ = is equal to 1 if tank q feeds CDU u during slot s
- $yq_{q,s}$ = is equal to 1 if tank q is delivering crude during slot s
- $zq_{q,s,e}$ = is equal to 1 if tank q is idle or settling during slot s under scenario e

3.3 Constraints

A vessel is unloaded during a slot s if it was unloading during the previous slot and has not finished yet, or if it starts at the beginning of the current slot (1).

$$xb_{b,s,e} = xb_{b,s-1,e} + xid_{b,s,e} - xfd_{b,s-1,e}$$
$$\forall b \in B, \forall s \in S, \forall e \in E \quad (1)$$

A ship can only undock if it is currently docked (2).

$$xb_{b,s,e} \geq xfd_{b,s,e} \quad \forall b \in B, \forall s \in S, \forall e \in E \quad (2)$$

Each vessel can be docked and undocked only once during the planning horizon, (3) and (4) respectively.

$$\sum_s xid_{b,s,e} = 1 \quad \forall b \in B, \forall e \in E \quad (3)$$

$$\sum_s xfd_{b,s,e} = 1 \quad \forall b \in B, \forall e \in E \quad (4)$$

Only one vessel can unload at any moment (assumption 1).

$$\sum_b xb_{b,s,e} \leq 1 \quad \forall s \in S, \forall e \in E \quad (5)$$

A maximum of two tanks can be loaded simultaneously (assumption 5).

$$\sum_q xq_{q,s,e} \leq 2 \quad \forall s \in S, \forall e \in E \quad (6)$$

A vessel cannot be docked if there is no tank receiving crude.

$$\sum_q xq_{q,s,e} \geq xb_{b,s,e} \quad \forall b \in B, \forall s \in S, \forall e \in E \quad (7)$$

A tank cannot be loaded if there is no vessel docked.

$$xq_{q,s,e} \leq \sum_b xb_{b,s,e} \quad \forall q \in Q, \forall s \in S, \forall e \in E \quad (8)$$

A tank may not charge more than two CDUs simultaneously (assumption 6).

$$\sum_u y_{q,u,s} \leq 2 \quad \forall q \in Q, \forall s \in S \quad (9)$$

At most three tanks are allowed to concurrently feed a CDU (assumption 7).

$$\sum_q y_{q,u,s} \leq 3 \quad \forall u \in U, \forall s \in S \quad (10)$$

Each CDU must continually process feedstock coming from tanks (assumption 9).

$$\sum_q y_{q,u,s} \geq 1 \quad \forall u \in U, \forall s \in S \quad (11)$$

A tank must be in one of the three states during a given slot.

$$xq_{q,s,e} + yq_{q,s} + zq_{q,s,e} = 1 \quad \forall q \in Q, \forall s \in S, \forall e \in E \quad (12)$$

A tank must be discharging if it is feeding a CDU (13) and vice versa (14).

$$yq_{q,s} \geq y_{q,u,s} \quad \forall q \in Q, \forall u \in U, \forall s \in S \quad (13)$$

$$\sum_u y_{q,u,s} \geq yq_{q,s} \quad \forall q \in Q, \forall s \in S \quad (14)$$

The end-time of a slot is equal to its start-time plus its length.

$$ts_s = is_s + ds_s \quad \forall s \in S \quad (15)$$

The start-time of a slot coincides with the end-time of the previous slot.

$$is_s = ts_{s-1} \quad \forall s \in S \quad (16)$$

The total length of the time slots must be equal to the length of the scheduling horizon.

$$\sum_s ds_s = H \quad (17)$$

The big-M method, explained by Winston and Goldberg (2004), is applied to compute the amount of crude unloaded to tanks (18)-(21).

$$fcbq_{c,b,q,s,e} \leq \overline{FQ}_q * ds_s$$
$$\forall q \in Q, \forall c \in C, \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (18)$$

$$fcbq_{c,b,q,s,e} \geq \underline{FQ}_q * ds_s - M1 * (2 - xb_{b,s,e} - xq_{q,s,e})$$
$$\forall q \in Q, \forall c \in C, \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (19)$$

$$fcbq_{c,b,q,s,e} \leq M1 * xb_{b,s,e}$$
$$\forall q \in Q, \forall c \in C, \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (20)$$

$$fcbq_{c,b,q,s,e} \leq M1 * xq_{q,s,e}$$
$$\forall q \in Q, \forall c \in C, \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (21)$$

Also, we use the big-M method to calculate the crude volume unloaded from a vessel during a slot s.

$$fcb_{c,b,s,e} \leq \overline{FB}_b * ds_s \quad \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (22)$$

$$fcb_{c,b,s,e} \geq \underline{FB}_b * ds_s - M2 * (1 - xb_{b,s,e})$$
$$\forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (23)$$

$$fcb_{c,b,s,e} \leq M2 * xb_{b,s,e} \quad \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (24)$$

The crude volume unloaded from a vessel during a slot s is equal to the sum of volumes unloaded to each tank.

$$fcb_{c,b,s,e} = \sum_q fcbq_{c,b,q,s,e} \quad \forall (b,c) \in BC, \forall s \in S, \forall e \in E \quad (25)$$

The total volume loaded into a tank during a slot s is calculated by using (26).

$$fbq_{b,q,s,e} = \sum_{c \in BC} fcbq_{c,b,q,s,e} \quad \forall b \in B, \forall q \in Q, \forall s \in S, \forall e \in E \quad (26)$$

To make each vessel unload fully during the scheduling horizon (assumption 2), we use (27).

$$\sum_s fcb_{c,b,s,e} = Vol_{b,c} \quad \forall (b,c) \in BC, \forall e \in E \quad (27)$$

The big-M method is applied to compute the amount of crude unloaded from tanks (28)-(30).

$$fqu_{q,u,s} \leq \overline{OFQ}_q * ds_s \quad \forall q \in Q, \forall u \in U, \forall s \in S \quad (28)$$

$$fqu_{q,u,s} \geq \underline{OFQ}_q * ds_s - M3 * (1 - y_{q,u,s})$$
$$\forall q \in Q, \forall u \in U, \forall s \in S \quad (29)$$

$$fqu_{q,u,s} \leq M3 * y_{q,u,s} \quad \forall q \in Q, \forall u \in U, \forall s \in S \quad (30)$$

The total volume unloaded from a tank during a slot s is calculated by using (31). It should be noted that this total volume does not depend on the scenarios as it is a first-stage variable. However, its composition does, as the inventory profile in each tank may be different between scenarios due to receiving crude from ships at different times.

$$fqu_{q,u,s} = \sum_c fcqu_{c,q,u,s,e} \quad \forall q \in Q, \forall u \in U, \forall s \in S, \forall e \in E \quad (31)$$

The total feed to CDU u during slot s is calculated by using (32)-(33).

$$fu_{u,s} = \sum_q fqu_{q,u,s} \quad \forall u \in U, \forall s \in S \quad (32)$$

$$\underline{FU}_u * ds_s \leq fu_{u,s} \leq \overline{FU}_u * ds_s \quad \forall u \in U, \forall s \in S \quad (33)$$

The concentration of key components in the feedstock for the CDUs is given by (34)-(35).

$$\sum_q \sum_c fcqu_{c,q,u,s,e} * PR_{c,k} \leq \overline{PROP}_{u,k} * fu_{u,s}$$
$$\forall k \in K, \forall u \in U, \forall s \in S, \forall e \in E \quad (34)$$

$$\sum_q \sum_c fcqu_{c,q,u,s,e} * PR_{c,k} \geq \underline{PROP}_{u,k} * fu_{u,s}$$
$$\forall k \in K, \forall u \in U, \forall s \in S, \forall e \in E \quad (35)$$

The amount of crude c in each tank at the start of slot s is calculated by using (36).

$$ic_{q,c,s,e} = ic_{q,c,s-1,e} + \sum_{b \in BC} fcbq_{c,b,q,s-1,e} - \sum_u fcqu_{c,q,u,s-1,e}$$
$$\forall q \in Q, \forall c \in C, \forall s \in S \setminus \{s1\}, \forall e \in E \quad (36)$$

The amount of crude c in each tank at the beginning of the horizon is given by (37).

$$ic_{q,c,s,e} = IIC_{q,c} \quad \forall q \in Q, \forall c \in C, s = s1, \forall e \in E \quad (37)$$

The amount of crude c in each tank at the end of the horizon is given by (38).

$$ice_{q,c,s,e} = ic_{q,c,s,e} + \sum_{b \in BC} fcbq_{c,b,q,s,e} - \sum_u fcqu_{c,q,u,s,e}$$
$$\forall q \in Q, \forall c \in C, s = |S|, \forall e \in E \quad (38)$$

The total crude level in each tank at the start of slot s ($i_{q,s,e}$) and at the end of the horizon ($ie_{q,s,e}$) is given by (39)-(42).

$$i_{q,s,e} = i_{q,s-1,e} + \sum_b fbq_{b,q,s-1,e} - \sum_u fqu_{q,u,s-1}$$
$$\forall q \in Q, \forall s \in S \setminus \{s1\}, \forall e \in E \quad (39)$$

$$ie_{q,s,e} = i_{q,s,e} + \sum_b fbq_{b,q,s,e} - \sum_u fqu_{q,u,s}$$
$$\forall q \in Q, s = |S|, \forall e \in E \quad (40)$$

$$i_{q,s,e} = \sum_c ic_{q,c,s,e} \quad \forall q \in Q, \forall s \in S, \forall e \in E \quad (41)$$

$$ie_{q,s,e} = \sum_c ice_{q,c,s,e} \quad \forall q \in Q, s = |S|, \forall e \in E \quad (42)$$

In order to not exceed the established page limit, we do not specify the mathematical formulation of the maximum and minimum volume constraints for tanks.

To ensure minimum settling time (assumption 4), we use (43).

$$is_{sbis} - ts_s \geq ST * (xq_{q,s,e} + yq_{q,sbis} - 1)$$
$$\forall q \in Q, \forall s \in S, \forall sbis \in S, s < sbis, \forall e \in E \quad (43)$$

To calculate the difference between processed volume and required demand by each CDU, we use (44)-(45).

$$op_u \geq \sum_s fu_{u,s} - dem_u \quad \forall u \in U \quad (44)$$

$$sp_u \geq dem_u - \sum_s fu_{u,s} \quad \forall u \in U \quad (45)$$

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

$$is_s \geq AT_{b,e} * xid_{b,s,e} \quad \forall b \in B, \forall s \in S, \forall e \in E \quad (46)$$

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

$$dmgs_{b,s,e} \geq is_s - AT_{b,e} * xid_{b,s,e} - H * (1 - xid_{b,s,e})$$
$$\forall b \in B, \forall s \in S, \forall e \in E \quad (47)$$

$$dmg_{b,e} = \sum_s dmgs_{b,s,e} \quad \forall b \in B, \forall e \in E \quad (48)$$

The variable $dep_{b,s,e}$ represents the departure time of vessel v in scenario e. If vessel v leaves the terminal after its expected departure time $EDT_{b,e}$, it should pay a penalty that will be proportional to the departure tardiness $tdn_{b,e}$. The values of the mentioned variables are defined by 49−51.

$$ts_s \leq dep_{b,s,e} + H * (1 - xfd_{b,s,e}) \quad \forall b \in B, \forall s \in S, \forall e \in E \quad (49)$$

$$tdns_{b,s,e} \geq dep_{b,s,e} - EDT_{b,e} \quad \forall b \in B, \forall s \in S, \forall e \in E \quad (50)$$

$$tdn_{b,e} = \sum_s tdns_{b,s,e} \quad \forall b \in B, \forall e \in E \quad (51)$$

The concentration of crudes sent to CDUs must be the same as the one inside the tank. This principle is satisfied by (52). It should be noted that this equation yields two bilinear terms.

$$i_{q,s,e} * fcqu_{c,q,u,s,e} = ic_{q,c,s,e} * fqu_{q,u,s}$$
$$\forall c \in C, \forall q \in Q, \forall u \in U, \forall s \in S, \forall e \in E \quad (52)$$

The cost associated with each scenario e is calculated by using (53). The first term, the costs due to the difference between processed volume and required demand, comprises the first-stage cost. The second term, demurrage and departure tardiness costs, represents the second-stage cost.

$$ze_e = \sum_u (COP_u * op_u + CSP_u * sp_u)$$
$$+ \sum_b (CDMG_b * dmg_{b,e} + CTDN_b * tdn_{b,e}) \quad \forall e \in E \quad (53)$$

The objective function, which is composed of the first-stage cost and the expected value of the second-stage cost, considering all scenarios e, is given by (54).

$$MIN \sum_e \pi_e * ze_e \quad (54)$$

4. RISK MANAGEMENT

Quite often, it is important to consider not only the expected value of a cost function J but its distribution and the risk of having values located in the upper tail of the distribution. There are two popular risk measures, Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR). On the one hand, VaR at confidence level $1-\alpha$ determines the minimum value ω^* such that the probability of J being lower than ω^* is larger than $1-\alpha$. On the other hand, CVaR at confidence level $1-\alpha$ is the average value of the tail of the distribution, above VaR. In this paper, we use CVaR because it is easier to compute and it is a more consistent measure of risk since, if J is convex with respect to u (decision variables), then CVaR is also convex.

Assuming a set of scenarios e with probabilities π_e, a risk constrained scheduling problem can be reformulated as follows:

$$ze_e - var \leq \phi_e \quad \forall e \in E \quad (55)$$

$$cvar = var + (1/\alpha) * (\sum_e \pi_e * \phi_e) \quad (56)$$

One of the main approaches in the practice of decision-making under risk uses mean-risk models. Here we minimize the mean-risk function (57) subject to (1)-(53), (55), and (56). In this approach, the parameter λ is a nonnegative trade-off coefficient representing the exchange rate of mean cost for risk (Noyan, 2012).

$$MIN \sum_e \pi_e * ze_e + \lambda * cvar \quad (57)$$

5. SOLUTION PROCEDURE

The solution procedure for the MINLP model consists of two stages. First, solving an MILP model which is an approximation of the MINLP formulation. Next, after fixing the binary variables of the original MINLP model to their optimal MILP values, the resulting NLP model is solved. In case no feasible solution can be reached, an outer approximation solver (DICOPT) is adopted. The approximate MILP formulation is obtained by replacing the nonlinear constraint (52) with the linear constraints (58) and (59) which state that a tank maintains the initial crude c concentration until the moment it receives crude oil from a ship.

$$fcqu_{c,q,u,s,e} \leq CONC_{q,c} * fqu_{q,u,s} + M4 * \sum_{s' \leq s} xq_{q,s',e}$$
$$\forall c \in C, \forall q \in Q, \forall u \in U, \forall s \in S, \forall e \in E \quad (58)$$

$$fcqu_{c,q,u,s,e} \geq CONC_{q,c} * fqu_{q,u,s} - M4 * \sum_{s' \leq s} xq_{q,s',e}$$
$$\forall c \in C, \forall q \in Q, \forall u \in U, \forall s \in S, \forall e \in E \quad (59)$$

6. RESULTS

In order to check the effectiveness of the proposed approach, a case study is carried out. It consists of a scheduling horizon of 120 hours, a refinery with 5 storage tanks, 2 CDUs, and 5 types of crude characterized by a single key property. In addition, the arrival of 2 ships is considered. The arrival times and probabilities for each scenario are detailed in Table 1. The expected departure date is 12 hours after the arrival. The demand for CDU 1 is 100,000 m^3 and for CDU 2 is 65,000 m^3. The example has been solved using GAMS software, CPLEX 32.2.0 for MILPs and CONOPT 4.19 for NLPs on an HPE server, Proliant DL380 with 2 processors and 32GB RAM. The total number of constraints, continuous, and binary variables are 19729, 9501, and 1272, respectively.

Table 1. Arrival times and probabilities

Scenarios	Probabilities	Arrival time (h)	
		Vessel 1	Vessel 2
1	0.01	10	40
2	0.05	50	40
3	0.01	90	40
4	0.18	10	70
5	0.5	50	70
6	0.18	90	70
7	0.01	10	100
8	0.05	50	100
9	0.01	90	100

Four values of α and three of λ were adopted. Twelve instances were solved from the combination of these values. The resolution of each of them took approximately 10 minutes. The results obtained are summarized in Table 2 and Table 3.

Table 2. CVaR values

CVaR (x10^3 $)	α			
λ	0.3	0.2	0.1	0.05
0	81.4	122.1	244.2	488.4
0.1	54.2	69.3	108.6	159
1	42.5	48.75	55.9	57

Table 3. Mean-risk function values

MR (x10^3 $)	α			
λ	0.3	0.2	0.1	0.05
0	24.42	24.42	24.42	24.42
0.1	29.84	31.35	35.28	40.32
1	76.04	82.29	96.8	97.53

In addition, Gantt charts for vessels operations corresponding to two instances are shown in Figure 2 and Figure 3.
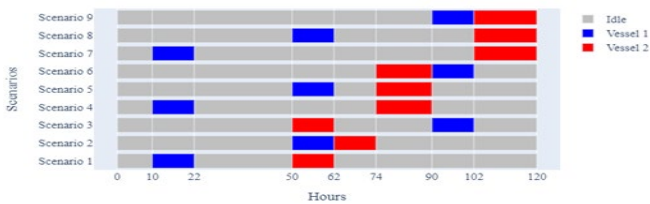

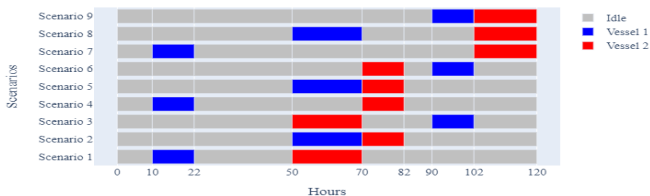Figure 2. Gantt chart ($\alpha = 0.3$, $\lambda = 1$).

Figure 3. Gantt chart ($\alpha = 0.3$, $\lambda = 0.1$).

Here we discuss how these risk parameters α and λ affect the solutions. When α decreases, more conservative policies are adopted, which give more weight to worse scenarios. Thus, the optimal mean-risk function of the total cost and CVaR increase. Increasing the value of λ implies a higher level of risk aversion as this means increasing the relative importance of the risk term. Similar to the parameter α, CVaR increases as λ decreases. However, the optimal mean-risk function increases as λ takes larger values.

7. CONCLUSIONS

A model characterizing the operation of a maritime terminal connected to an oil refinery has been presented. The model is used to decide the best way of operating the crude section taking into account the uncertainty associated with the arrival of ships. The benefits of considering, at once, a two-stage stochastic approach, CVaR and continuous-time formulation applied to the optimization of crude oil operations scheduling are summarized below. The two-stage formulation provides a more robust solution since this approach allows correct the consequences of decisions taken now depending on future conditions. On the other hand, the incorporation of CVaR makes it possible to penalize extreme values and thus minimize risk. Then, although the continuous-time formulation is usually more complicated to develop, compared to the discrete one, it represents the operations with a higher degree of accuracy and with a smaller number of elements and variables. Finally, even though the solution of the approximate MILP model might not be optimal for the MINLP, it provides an efficient way of selecting very good and feasible decisions according to the risk level the user wishes to assume.

8. ACKNOWLEDGEMENTS

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