Preprints of the 10th IFAC International Symposium on Dynamics and Control of Process Systems
The International Federation of Automatic Control
December 18-20, 2013. Mumbai, India

Short-term scheduling of diesel blending and distribution

Diovanina Dimas * **Valéria V. Murata** * **Sérgio M. S. Neiro** *

* *Federal University of Uberlândia, School of Chemical Engineering, Uberlândia, Brazil (e-mail: sergioneiro@feq.ufu.br)*

Abstract:
The present work is concerned with the development of alternative optimization models which address the scheduling problem of diesel blending and distribution in oil-refinery operations. The problem involves intermediate products stored in dedicated tanks that are blended to produce diesel with three different grades. The final products are then shipped to final destination through pipelines. Our study starts by revisiting a model originally proposed in the literature by Pinto et al. (2000). Next, improvements mainly concerning with the interface identification constraints are proposed and evaluated with the intention to extend the model applicability. Three different approaches were proposed. Results demonstrate that the introduction of penalties as to pumping interruptions produce good results enabling the formulations to be applied in cases where the time horizon is extended.

Keywords: Optimization, scheduling and transition cost.

1. INTRODUCTION

In recent years, with growing demand for petroleum products, tighter enviromental regulations and increasing market competition it is imperative to improve operations management of petroleum refining industry as a whole (Guyonnet et al., 2009). An outstanding feature of the petroleum industry is the integrated behavior of chemical processes as a consequence of continuous processing with uninterrupted production (Tavares, 2005). This dynamic feature makes clear the key role of optimization in producing efficient production plans and schedules that enable greater profitability.

According to Reklaitis (2000) production planning and scheduling define what, when, where and how to produce a set of different products along a time horizon. Typically, planning is concerned with production, distribution, sales and inventory plans based on future demands and market information (Kallrath, 2002). On the other hand, scheduling involves allocation of a set of limited resourses, activities sequencing and processing time determination (Soares, 2009).

Generally, in oil industry several intermediate streams are generated by processing units whose qualities depend on crude oil properties and operating conditions. These intermediate streams are processed in downstream units or blended to compose finished products whose qualities depend on the amount of each intermediate stream that participates in the recipe (Coxhead, 1994). The scheduling is normally applied to subsystems of the refinery due to the high degree of complexity arising when the problem is treated as a whole. Shah et al. (2011) decompose the refinery scheduling problem in three subsystems: (i) crude-oil unloading, mixing and inventory control; (ii) production unit scheduling, and (iii) finished product blending and shipping. Most of the reported literature concentrates in the first subsystem.

In this work, a mathematical formulation is proposed which addresses the diesel blending and distribution subsystem. As far as the distribution is concerned, parcels of diesel with different grades are pumped sequentially in the same pipeline, which create interface zones between consecutive products. The interface degrades product quality and, therefore, reducing the number of interfaces to a minimum is a desired task. The main concern of this work is to propose different approaches for identifying transitions in pipelines while final products are blended to satisfy quality especification and market demand. A study that allow shipping a product more than once over the time horizon is also performed. These are preliminary studies that aim at developing a generic model can be applied to further studies using a longer time horizon.

2. PROBLEM STATEMENT

The formulation introduced by Pinto et al. (2000) for diesel blending and distribution problem was taken as a starting point for our development, which is presented in the next section. Fig. 1 depicts a general description of the elements involved in the problem scope. The three distillation units provide intermediate streams that are sent to six dedicated storage tanks. After blending, final products may be distributed through three pipelines available. Actually, each pipeline is devoted to satisfy a specific market which presents specific demand profile.

2.1 Mathematical Model

The mathematical model is built based on the discrete time representation, in which the time horizon is dis-

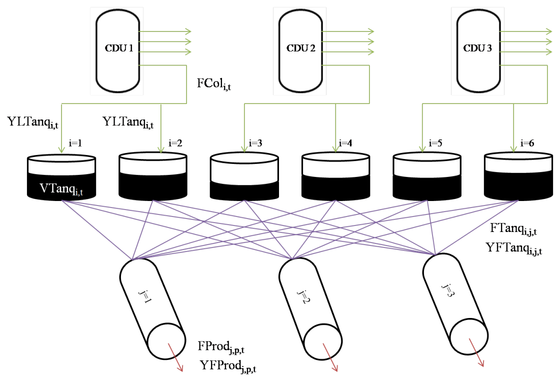

Fig. 1. Diesel blending and distibution problem.

cretized in 24 time periods of 1 hour each. What follows is a summary of the operating rules and general assumptions:

(1) There are two tanks connected to each distillation unit;
(2) Each tank i can store only one intermediate product;
(3) Parallel rundown tanks are not allowed to load simultaneously;
(4) A tank is not allowed to load and unload simultaneously;
(5) Full connection is established between tanks and pipelines;
(6) Properties of intermediate products are assumed to remain unchanged along the entire time horizon;
(7) Each pipeline j can recieve intermediate produtcs from multiple tanks, but is just allowed to ship final product p only once along the entire time horizon;
(8) Blend only occurs at the pipeline feed point just before shipping (in-line blending);
(9) Mixture properties are estimated based on the volume weighted average properties of intermediate streams;
(10) Diesel parcels with different grades shipped sequencially gives rise to an interface which incurs costs;
(11) Intermediate streams are assumed to present close density values and mixtures are assumed to be ideal.

2.2 Pinto et al. (2000) Model - Pinto's

The objective function is to minimize operating costs, which include material cost (CRM_i), pumping cost (CP_i), inventory cost ($CINV_i$) and transition cost ($TRAN_{j,p,n}$), as given by equation (1).

$$
\begin{aligned}
Min = & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}[(CRM_i + CP_i)\cdot FTanq_{i,j,t}] + \\
& + \sum_{i=1}^{I}\sum_{t=1}^{T}(CINV_i \cdot VTanq_{i,t}) + \\
& + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{n=1}^{N}(Ctran_{p,n}\cdot TRAN_{j,p,n})
\end{aligned} \tag{1}
$$

Subject to:

Material Balance Constraints: The total amount of material in each tank i as well as their storage capacities are gived by equations (2) and (3).

$$VTanq_{i,t} = V0_i + \sum_{t'=1}^{t'\leq t}\left[FCol_{i,t'} - \sum_{j=1}^{J}(FTanq_{i,j,t'})\right] \tag{2}$$

$i = 1, ..., I$ e $t = 1, ..., T$

$$VTanq_i^{MIN} \leq VTanq_{i,t} \leq VTanq_i^{MAX} \tag{3}$$

$i = 1, ..., I$ e $t = 1, ..., T$

Equation (4) is an overall material balance between tanks and pipelines which sets total amount of final product equal to the amounted lifted from each storage tank. Note that only one of the $FProd$ variables will be nozero in the sum on the left hand side of the equation (4) since only one product can be blended at a time (see equation 14). Equation (5), on the other hand, presents the key-component material balance.

$$\sum_{p=1}^{P} FProd_{j,p,t} = \sum_{i=1}^{I} FTanq_{i,j,t} \tag{4}$$

$j = 1, ..., J$ e $t = 1, ..., T$

$$\sum_{p=1}^{P}(C_{p,k}\cdot FProd_{j,p,t}) = \sum_{i=1}^{I}(ES_{i,k}\cdot FTanq_{i,j,t}) \tag{5}$$

$j = 1, ..., J,\ k = 1, ..., K$ e $t = 1, ..., T$

Where $C_{p,k}$ is the specification value of key-componet k for product p and $ES_{i,k}$ is the composition of key-component k in tank i.

Demand Constraints: The amount of product p sent by pipeline j throughout the time horizon must be exactly equal to the demand of that product, as given by equation (6).

$$DM_{j,p} = \sum_{t=1}^{T} FProd_{j,p,t} \tag{6}$$

$j = 1, ..., J$ e $p = 1, ..., P$

Operating Rules: Equation (7) forbids simultaneous loading of parallel tanks by a column, where . Equation (8) guarantees that a tank does not load and unload simultaneously. NC^i imposes an upper limit on the number of pipelines each tank i can feed.

$$YLTanq_{i,t} + YLTanq_{i+1,t} = 1 \tag{7}$$

$i = 1, 3, 5, ...$ e $t = 1, ..., T$

$$NC_i \cdot YLTanq_{i,t} + \sum_{j=1}^{J_i} YFTanq_{i,j,t} \leq NC_i \tag{8}$$

$i = 1, ..., I$ e $t = 1, ..., T$

Where $YLTanq_{i,t}/YFTanq_{i,j,t}$ denotes if tank i is loading/feeding pipeline j at time t and J_i is the set of pipelines that can be loaded by tank i.

Product p is pumped through pipeline j only once along the entire time horizon as stated by equation (9).

$$\sum_{t=1}^{T} YPipeI_{j,p,t} \leq 1 \tag{9}$$

$j = 1, ..., J$ e $p = 1, ..., P$

Equation (10) enforces the activation of two binary variables; one for the start and another for the end of the feeding operation, whereas equation (11) ensures that those events will be ordered correctly.

$$\sum_{t=1}^{T} (YPipeI_{j,p,t} - YPipeF_{j,p,t}) = 0 \quad (10)$$

$j = 1, ..., J$ e $p = 1, ..., P$

$$\sum_{t=1}^{T} (t \cdot YPipeI_{j,p,t}) = ti_{j,p} \leq tf_{j,p} = \sum_{t=1}^{T} (t \cdot YPipeF_{j,p,t}) \quad (11)$$

$j = 1, ..., J$ e $p = 1, ..., P$

Where $YPipeI_{j,p,t}/YPipeF_{j,p,t}$ denotes if pumping of product p at pipeline j has started/ended at time period t

Equation (12) is used to activate binary variables between t and t'corresponding to the time window in which product p is being pumped.

$$YFProd_{j,p,t} = \sum_{t'}^{t' \leq t} YPipeI_{j,p,t'} - \sum_{t'}^{t' < t} YPipeF_{j,p,t'} \quad (12)$$

$j = 1, ..., J$, $p = 1, ..., P$ e $t = 1, ..., T$

Where $YFProd_{j,p,t}$ denotes if product p is being transported by pipeline j at time period t.

According to equation (13), if product p is pumped by pipeline j there must be at least one tank feeding that pipeline. Equation (14) ensures that no more than one product will be pumped by a pipeline at a given time period.

$$YFTanq_{i,j,t} \leq \sum_{p=1}^{P} YFProd_{j,p,t} \quad (13)$$

$i = 1, ..., I$, $j = 1, ..., J$ e $t = 1, ..., T$

$$\sum_{p=1}^{P} YFProd_{j,p,t} \leq 1 \quad (14)$$

$j = 1, ..., J$ e $t = 1, ..., T$

Flowrate Constraints: Equations (15), (16) and (17) define minimum and maximum flowrate limits.

$$\begin{array}{l} Col_i^{MIN} \cdot YLTanq_{i,t} \leq FCol_{i,t} \\ FCol_{i,t} \leq Col_i^{MAX} \cdot YLTanq_{i,t} \end{array} \quad (15)$$

$i = 1, ..., I$ e $t = 1, ..., T$

$$\begin{array}{l} Tanq_{i,j}^{MIN} \cdot YFTanq_{i,j,t} \leq FTanq_{i,j,t} \\ FTanq_{i,j,t} \leq Tanq_{i,j}^{MAX} \cdot YFTanq_{i,j,t} \end{array} \quad (16)$$

$i = 1, ..., I$, $j = 1, ..., J$ e $t = 1, ..., T$

$$\begin{array}{l} Pipe_j^{MIN} \cdot YFProd_{j,p,t} \leq FProd_{j,p,t} \\ FProd_{j,p,t} \leq Pipe_j^{MAX} \cdot YFProd_{j,p,t} \end{array} \quad (17)$$

$j = 1, ..., J$, $p = 1, ..., P$ e $t = 1, ..., T$

Transition Constraints: When different final products are pumped sequentially an interface is established between the two products in which a portion of the product considered to be the most noble is degraded and, therefore, a transition cost must be incurred to account for this product degradation.

The variable $TRANS_{j,p,n}$ is used to identify a potential transition between final products p and n based on the start and finish pumping times of the two products as stated by Equations (18) and (20). Obviously, there is no transition when products p and n are the same, as given by equation (19).

$$TRANS_{j,p,n} \geq (ti_{j,n} - ti_{j,p}) / T \quad (18)$$

$n \neq p$, $p = 1, ..., P$ e $j = 1, ..., J$

$$TRANS_{j,p,n} = 0 \quad (19)$$

$n = p$, $p = 1, ..., P$ e $j = 1, ..., J$

$$-T \cdot (1 - TRANS_{j,p,n}) \leq (ti_{j,n} - ti_{j,p}) \quad (20)$$

$n \neq p$, $p = 1, ..., P$ e $j = 1, ..., J$

The variable $TRAN$ is used to identify which of the transitions indeed occur. Equation (21) states that if there is no potential for a transition, variable $TRAN$ will never be activated. Equations (22) and (23) complement equation (21) in that they force variable $TRAN$ to zero in case there is no demand for product p/n at pipeline j, i. e., $NT_{j,p} = 0$ or $NT_{j,n} = 0$.

$$TRAN_{j,p,n} \leq TRANS_{j,p,n} \quad (21)$$

$p = 1, ..., P$, $n = 1, ..., N$ e $j = 1, ..., J$

$$\sum_{n=1}^{N} TRAN_{j,p,n} \leq NT_{j,p} \quad (22)$$

$p = 1, ..., P$, e $j = 1, ..., J$

$$\sum_{p=1}^{P} TRAN_{j,p,n} \leq NT_{j,n} \quad (23)$$

$n = 1, ..., N$ e $j = 1, ..., J$

Equation (24) limits the number of transitions to the maximum number of transitions dictated by the demand input data.

$$\sum_{p=1}^{P} \sum_{n=1}^{N} TRAN_{j,p,n} = NTRAN_j \quad (24)$$

$j = 1, ..., J$

Where the parameter $NTRAN$ is calculated by Equation (25):

$$NTRAN_j = max \left(0, \sum_{p=1}^{P} NT_{j,p} - 1 \right) \quad (25)$$

3. PROPOSED APPROACHES

This section is concerned with modifications done to Pintos model and its imediate extension as to the length of the time horizon. Alternative constraints for transition identification that do not rely on the information about the start/end pumping time are proposed. In that case, multiple shipping considering the same product is allowed along the time horizon, which enables application of time horizons which represents more realistic cases. When the constraint of single shipment for each product is dropped, excessive transitions are avoied based on just transition costs.

3.1 For transition identification

Model 1

In the first approach, the variable $TRANS$ together with equations (18) - (24) are dropped from the base model and are replaced by constraint (26). This constraint has been extensively used in optimization formulation problems for transition identification between consecutive time periods.

$$TRAN_{j,p,n} \geq (YFProd_{j,p,t} + YFProd_{j,n,t+1} - 1) \quad (26)$$

$j = 1, ..., J$, $p = 1, ..., P$, $n = 1, ..., N$, $t = 1, ..., T$ e $p \neq n$

Model 2

There is an evident flaw in the first approach in that equation (26) will not be able to identify transitions if different tasks are allocated in time periods that are not adjacent. Therefore, in the second approach, constraint (26) is modified to be able to identify transitions even when they are established between time periods that are further apart. It should be noted that the third term on the right hand side of equation (27) is added to keep feasibility when time periods t and t' are not consecutive. In that case, if different tasks are allocated to time periods t and t' and if any task is allocated between t and t' the third term assumes an integer value different from zero causing the constraint to always be satisfied, otherwise the transition will be correctly identified.

$$\begin{aligned} TRAN_{j,p,n} \geq\ & YFProd_{j,p,t} + YFProd_{j,n,t'} + \\ & - \sum_{p'=1}^{P} \sum_{t''=t+1}^{t'-1} YFProd_{j,p',t''} - 1 \end{aligned} \quad (27)$$

$j = 1, ..., J$, $p = 1, ..., P$, $n = 1, ..., N$, $t = 1, ..., T$, $t' > t$ e $p \neq n$

Model 3

Equation (26) is simple but may fail to identify transitions if idle time periods are allocated between time periods where different operations are acomplished. Equation (27) is able to circumvent the downside of the first approach. However, this is done at the expense of an increase in the number of constraints. The third approach is conceptually a mix of the last two approaches. On one hand, in this approach only consecutive time periods are evaluated in the transition identification (equation 28). On the other hand a new variable is introduced for conveying the information on the last active operation before the resource developing the operation went idle.

Therefore, in the context of the pipeline operations schedule, at any point in time a pipeline might be either pumping a product or idle, in which case the $STOP$ variable is activated. This is guaranteed by equation (30). Equation (29) is used to transfer the information of which product was being pumped by the pipeline before it went idle. Note that the variable $STOP$ appears on both sides of the constraint enabling the information to be carried over even if the pipeline remains idle for more than one time period. Therefore, although equation (28) always compare consecutive time periods, because of the introduction of variables $STOP$, operations that occurred far in the past are still accounted for.

$$\begin{aligned} TRAN_{j,p,n,t} \geq\ & YFProd_{j,p,t} + YFProd_{j,n,t+1} + \\ & + STOP_{j,p,t} + STOP_{j,n,t+1} - 1 \end{aligned} \quad (28)$$

$j = 1, ..., J$, $p = 1...P$, $n = 1...N$, $t = 1, ..., T$ e $p \neq n$

$$\begin{aligned} & \sum_{n=1}^{N} YFProd_{j,n,t+1} + STOP_{j,p,t+1} \geq \\ & STOP_{j,p,t} + YFProd_{j,p,t} \end{aligned} \quad (29)$$

$j = 1, ..., J$, $p = 1...P$, $t = 1, ..., T$ e $t < 24$

$$\sum_{p=1}^{P} YFProd_{j,p,t} + \sum_{p=1}^{P} STOP_{j,p,t} = 1 \quad (30)$$

$j = 1, ..., J$ e $t = 1, ..., T$

The variable $STOP$ indicates when pipelines are idlle, which is an undesired situation given than the greater the idle time the higher the mixing promoted at the interface zones. Therefore, Model 3 was also ran with an additional penalty term that accounts for stopage at pipelines. The corresponding results are referred to as Model 3a.

3.2 Multiple Shipping Models

The formulation originally introduced by Pinto et al. (2000) was built relying on the fact that due to the very short time horizon involved (1 day) final products are allowed to be shipped only once along the entire time horizon (Equation 9). Therefore, the amount of each diesel parcel pumped through pipelines equals the amount demanded by the regional marked served by the pipeline. Also, the transition identification constraints are build based on the start of the pumping operations, relying again on the fact that each product can be handled only once by each pipeline. In real world problems, however, the length of the time horizon usually involves a few days or weeks, in which case the demand of each final product might be split into multiple parcels, i.e, the same final product is shipped multiple times.

Since we aimed at extending the application of Pinto's formulation to more realistic problems, we have also tested the proposed approaches in the previous section (Models 1, 2, 3 and 3a), allowing multiple shipments. This study requires removal of the equations 9 through 12 and 24, generating the models 4, 5, 6 and 6a, respectively. Here, like in Model 3, is tested the influence of the $STOP$ variable on the objetive function for Model 6, producing the Model 6a.

Table 1 presents a summary of the equations that compose each formulation.

4. RESULTS AND DISCUSSION

All formulations result in MILP problems which were implemented using the GAMS 23.7 system and the CPlex

Table 1. Summary of model equations.

Model 1 - Equations (1)-(17) and (26)
Model 2 - Equations (1)-(17) and (27)
Model 3 - Equations (1)-(17) and (28)-(30)
Model 4 - Equations (1)-(8), (13)-(17) and (26)
Model 5 - Equations (1)-(8), (13)-(17) and (27)
Model 6 - Equations (1)-(8), (13)-(17) and (28)-(30)

solver on an Intel(R) Core(TM)2 Quad CPU 2.66GHz, 2,0Gb RAM. Three diesel grades are produced depending on sulfur concentration and cetane number, namely: metropolitan (p=1), regular (p=2) and maritime (p=3). The input data is presented in Appendix A. Data on the dimension of each model is given in table 2, whereas results as to objective function values, CPU times and component costs are presented in table 3. Fig. 2 and 3 present a comparioson of the scheduling results.

Table 2. Models size.

	Equations	Bin. Var.	Total Var.
Pinto's	3,032	1,278	2,237
1	3,587	1,251	2,210
2	8,123	1,251	2,210
3	3,794	2,088	3,047
4	3,326	1,440	2,381
5	7,862	1,440	2,381
6	3,533	1,656	2,597

Table 3. Optimization results

Model	OF	CPU	Mat. cost	Pump. cost	Inv. cost	Transition cost
Pinto's	200.33	1.06	6.99	3.07	184.67	5.6
1	203.94	2.06	8.03	3.03	186.55	6.2
2	199.9	5.04	7.32	3.08	183.89	5.6
3	201.36	2.98	6.97	3.06	185.22	6.1
3a	199.93	1.97	7.25	3.08	183.90	5.7
4	197.43	0.98	7.17	3.08	184.29	2.9
5	203.03	5.01	6.88	3.06	185.59	7.5
6	201.45	2.68	6.77	3.05	185.93	5.7
6a	202.07	1.01	7.51	3.10	185.96	5.5

It can be observed from table 3 a fluctuation on the objective function values caused by variations of the cost components. The inventory cost represented the main cost components for all approaches. However, there was an exception for Model 5, that presented the highest transition cost. Model 2 resulted in an objective function similar to Pinto's Model, caused by reduction of inventory cost. Further, Model 4 had the lowest objective function value due to transition cost. Actually, in this approach, when an interruption is scheduled between pumping operations involving different products, transition cannot be identified. Therefore, the transition cost seen in table 3 for Model 4 is not real value. Results for Model 3a were a little better in terms of the objective function which was similar to Pinto's model. On the orther hand, Model 6a resulted in the lowest transition cost and solution time was better in comparison to all approaches. Also, it can be verified, in table 2, that the number of variables as well as the number of equations in Model 6a are greater than Pinto's model.

Fig. 2 and Fig. 3 show the pipeline operation. In both figures, the Gantt charts for the proposed approaches were done in comparison to Pinto's Model. Some approaches produced differents sequences in comparison to Pinto's

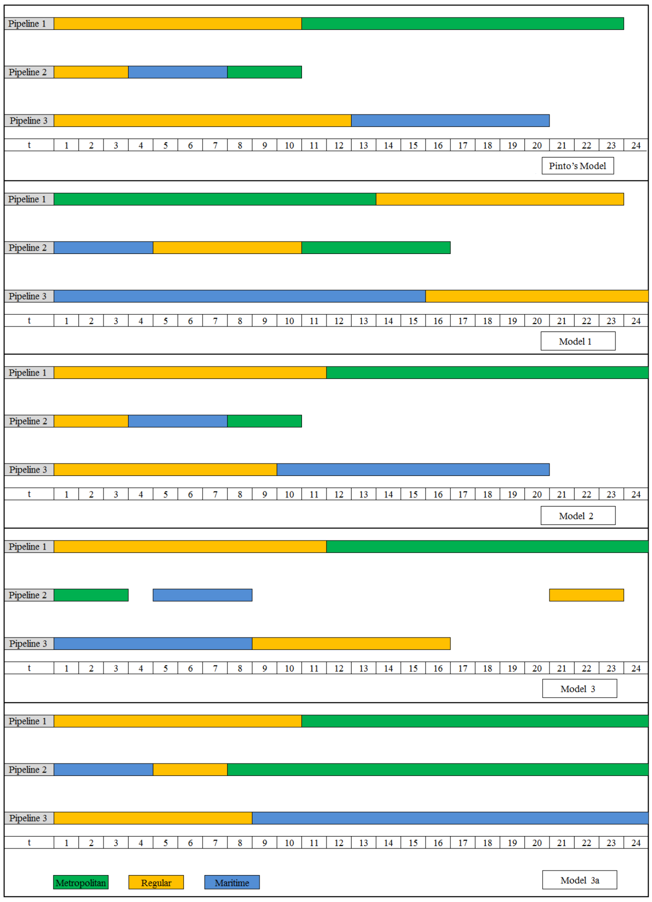

Fig. 2. Gantt chart for models 1, 2, 3 and 3a

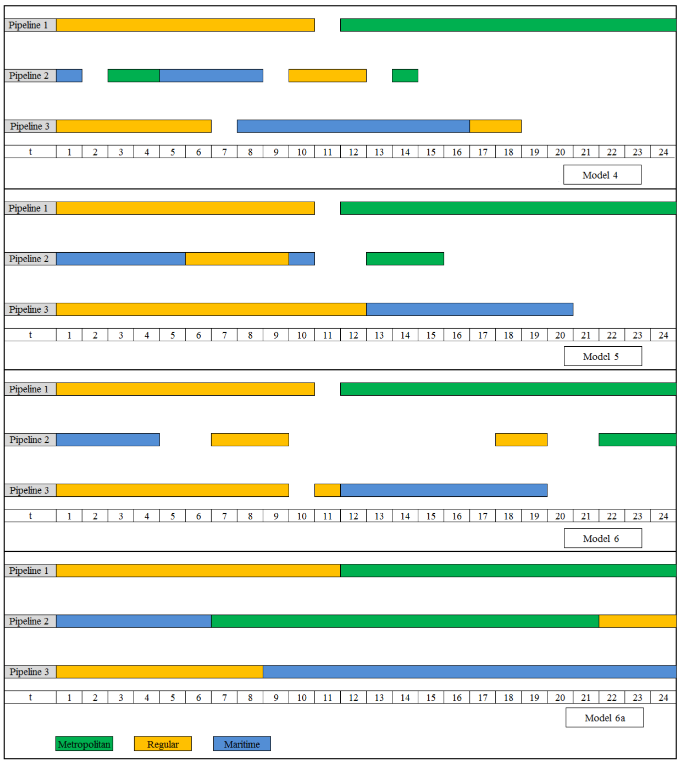

Fig. 3. Gantt chart for models 4, 5, 6 and 6a

Model. Also, some pipelines shipped products for a longer period of time, which was done by reducing pumping rate, whereas demand is constant. Model 2 produced the same sequence as Pinto's Model, consequently, similar objective function was obtained. Model 3 presented some interruptions in pipeline 2, so the operation is unfeasible from a pratical stand point.

Models 3a and 6a resulted in products shipment along the whole time horizon. These models applied penalties in the objective function, where stoppage is highly undesirable. Another important fact stands out in Fig. 3, Models 5 and 6 produced short pumping operations. Also, some interruptions between products shipment occur in Models 4, 5 and 6 which is undesirable in real world operations.

5. CONCLUSION

In this work, differents formulations were proposed as to identifying transitions, established when differents products are pumped one after another. Model 2 produced the best results in terms of the objective function. However, because of the large number of additional constraints it also resulted in poor computational peformance. The introduction of the varaiable $STOP$ into model 3a also caused this formulations to be very promissing for it was able to produce good scheduling results, objective function value and reasonable solution time. As for the case where multiple shipments are allowed, again the introduction of variable $STOP$ improves the scheduling quality, as well as, the solution time. The results here obtained are the starting point for further developments in the area of blending and distribuition of refinery operations.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support received from CAPES.

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Appendix A. INPUT DATA

Table A.1. Key component specifications.

Diesel Grade	Sulfur ($\%wt.$)	Cetane Number ($\%wt.$)
Metropolitan	≤ 0.3	≥ 42
Regular	≤ 0.5	≥ 40
Maritime	≤ 1.0	≥ 40

Table A.2. Input data for tanks.

Parameters/Tanks	1	2	3	4	5	6
Sulfur ($\%wt.$)	0.30	0.30	0.60	0.40	1.00	1.00
Cetane Number ($\%wt.$)	42.0	42.0	40.3	39.0	40.0	40.0
$VTanq_i^{min}(10^3m^3)$	2	2	2	2	2	2
$VTanq_i^{max}(10^3m^3)$	30	30	30	30	30	30
$Vo_i(10^3m^3)$	10	20	8	8	15	12
$Col_i^{MIN}(m^3/h)$	250	250	220	220	180	180
$Col_i^{MAX}(m^3/h)$	300	300	250	250	200	200
$Tank_{i,j}^{MIN}(m^3/h)$	30	30	40	40	40	40
$Tank_{i,j}^{MAX}(m^3/h)$	500	500	500	500	500	500
$CINV_i(\$*h/m^3)$	0.10	0.10	0.12	0.12	0.11	0.11
$CP_i(\$*h/m^3)$	0.20	0.20	0.18	0.18	0.16	0.16
$CRM_i(\$*h/m^3)$	0.60	0.60	0.40	0.40	0.05	0.05

Table A.3. Transition costs p/n (\$).

p/n	Metropolitan	Regular	Maritime
Metropolitan	0.0	1.1	1.0
Regular	1.3	0.0	1.2
Maritime	1.9	1.9	0.0

Table A.4. Demands (m^3).

Pipeline	Metropolitan	Regular	Maritime
$j = 1$	$5,000$	$4,000$	0
$j = 2$	$1,000$	$1,000$	$1,500$
$j = 3$	0	$2,000$	$2,000$