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APPENDICES

Appendix A Nomenclature.

Indices

t	Set of time periods
c	Set of all commodities
o	Set of crude oils
p	Set of products
i	Set of intermediates
u	Set of productive units
q	Set of properties
s	Set of scenarios

Parameters

$pro_{u,c,q}$	Property q of commodity c from unit u	
$px_{p,q}$	Maximum property q of product p	
$pn_{p,q}$	Minimum property q of product p	
$cyield_{o,c}$	Percent of component c in crude oil o	(%)
$yield_{u,c}$	Percent yield of commodity c from unit u	(%)
$dem_{p,t}$	Demand of product p in time period t	(m^3)
ux_u	Maximum capacity of unit u	(m^3)
un_u	Minimum capacity of unit u	(m^3)
ox_o	Maximum monthly purchase of crude oil o	(m^3)
on_o	Minimum monthly purchase of crude oil o	(m^3)
$stox_p$	Maximum storage capacity of product p	(m^3)
$cp_{p,t}$	Unit sale price of product p in time period t	($\$/m^3$)
$co_{o,t}$	Unit purchase price of crude oil o in time period t	($\$/m^3$)
$ci_{i,t}$	Unit purchase price of intermediate i in time period t	($\$/m^3$)
$cl_{p,t}$	Unit cost of lost demand penalty for product p in time period t	($\$/m^3$)
ρ_s	Probability of scenario s	
$density_u$	Density of feed to unit u	(ton/m^3)

$fuel_u$	Percent energy consumption for unit u based on tFOE	(%)
disc	Percent discount from normal price	(%)

Variables

$PO_{u,c,q,t}$	Property q of commodity c from unit u in time period t	
$AF_{u,t}$	Amount of feed to unit u in time period t	(m^3)
$AO_{u,c,t}$	Amount of outlet commodity c from unit u in time period t	(m^3)
$A_{u,c,u',t}$	Amount of commodity c flow between unit u and unit u' in time period t	(m^3)
$MANU_{p,t}$	Amount of product p produced in time period t	(m^3)
$AC_{o,t}$	Amount of crude oil o refined in time period t	(m^3)
$AI_{i,t}$	Amount of intermediate i added in time period t	(m^3)
$AS_{p,t}$	Amount of product p stored in time period t	(m^3)
$AL_{p,t}$	Amount of lost demand for product p in time period t	(m^3)
$AD_{p,t}$	Amount of discount product sold in time period t	(m3)
$Burnt_{p,t}$	Amount of product p burnt in time period t	(m^3)
$Used_t$	Amount of fuel used in time period t	(tFOE)
$TP_{p,t}$	Income from selling product p in time period t	($)
$TO_{o,t}$	Expense from purchasing crude oil o in time period t	($)
$TI_{i,t}$	Expense from purchasing intermediate in time period t	($)
$TS_{p,t}$	Expense from storage product p in time period t	($)
$TL_{p,t}$	Expense from lost demand of product p in time period t	($)
$TD_{p,t}$	Expense from discount sales of product p in time period t	($)
$sales_{p,t}$	Sales of product p in time period t	(m^3)

Appendix B Blending equation for each property.

The product properties used in this model can be calculated by based on the Equation (3.5). The following equations show how each property is calculated.

(1) Octane blending (Gary and Handwerk, 2001)

Octane numbers are blended on a volumetric basis using the blending octane numbers of the components. In practice true octane numbers do not blend linearly and it is necessary to use blending octane numbers in making calculations.

$$ON_{blend} = \sum V_i(ON)_i \quad \text{(B.1)}$$

where:

ON_{blend}	=	blending octane numbers of total blend
ON_i	=	blending octane numbers of component i
V_i	=	volume fraction of component i

(2) RVP blending (Baird, 1989)

The theoretical method for blending to the desired Reid vapor pressure requires that the average molecular weight of each of the streams be known. Although there are accepted ways of estimating the average molecular weight of a refinery stream from boiling point, gravity, and characterization factor, none of these methods lend themselves to use in linear programming models. A more convenient way is to use the empirical method developed by Chevron Research Company. Reid Vapor Pressure Blending Indices (RVPI) have been compiled as a function of the RVP of the blending streams. The Reid vapor pressure of the blend is closely approximated by the sum of all the products of volume fraction (V) times the RVPI for each component. The Chevron equation for RVP follows:

$$RVPI = RVP^{1.25} \quad \text{(B.2)}$$

$$RVPI_{blend} = \sum V_i(RVPI)_i \quad \text{(B.3)}$$

where:

RVP	=	Reid vapor pressure, psia
$RVPI_{blend}$	=	Reid vapor pressure blending indices of total blend
$RVPI_i$	=	Reid vapor pressure blending indices of component i
V_i	=	volume fraction of component i

(3) Aromatic blending (Baird, 1989)

Aromatic blending can be calculated by the sum of all products of volume fraction (V) times the aromatic content for each component.

$$\%Aro_{blend} = \sum V_i(\%Aro)_i \tag{B.4}$$

where:

$\%Aro_{blend}$	=	percent of aromatic content in total blend
$\%Aro_i$	=	percent of aromatic content in component i
V_i	=	volume fraction of component i

(4) Freezing point (Baird, 1989)

Maurin (1967) presents a direct method for the weight blending of freeze points. The freezing point of the blend can be approximated by the sum of all the products of weight fraction (W) times the freezing point index (FPI) for each component. The blending index numbers for this system are presented in Table B1.

$$FPI_{blend} = \sum W_i(FPI)_i \tag{B.5}$$

$$W_i = \frac{V_i \times S.G._i}{\sum V_i \times S.G._i} \tag{B.6}$$

where:

FPI_{blend}	=	freezing point indices of total blend
FPI_i	=	freezing point indices of component i
W_i	=	weight fraction of component i

V_i = volume fraction of component i

S.G.$_i$ = specific gravity of component i

(5) Cetane index blending (Baird, 1989)

Cetane number blending can be estimated linearly on the volume basis by the sum of all products of volume fraction (V) times the cetane blending index for each component. Although this is an approximate method, it can give the satisfactory result.

$$CI_{blend} = \sum V_i (CI)_i \tag{B.7}$$

where:

CI_{blend} = cetane indices of total blend

CI_i = cetane indices of component i

V_i = volume fraction of component i

(6) Viscosity blending (Baird, 1989)

Viscosity is not an additive property and it is necessary to use special techniques to estimate the viscosity of a mixture from the viscosities of its components. The use of blending index systems provides a much simpler approach to viscosity blending and is most often used in linear programming models to represent the viscosity blending of distillate and residual fuels. It is usually true to a satisfactory approximation that the viscosity blending index numbers (VBN) of the blend will be the sum of all the products of the weight fraction times the VBN for each component. In equation form:

$$VBN_{blend} = \sum (W_i \times VBN_i) \tag{B.8}$$

where:

VBN_{blend} = viscosity blending index numbers of total blend

VBN_i = viscosity blending index numbers of component i

W_i = weight fraction of component i

Blending of kinematic viscosities (centistokes) may be done at any temperature, but the viscosities of all components of the blend must be expressed at the same temperature. The Refutas system can be used to calculate VBN. The equations for the Refutas blending index numbers are as follows:

$$VBN = 10.975 + 14.535(\ln(\ln(CST + 0.8))) \quad \text{(B.9)}$$

$$CST = \exp(\exp((VBN - 10.975)/14.535)) - 0.8 \quad \text{(B.10)}$$

where:

VBN = viscosity blending index number

CST = viscosity in centistokes

(7) Sulfur blending (Maples, 2000)

Sulfur blending can be calculated linearly on the mass basis by the sum of all products of weight fraction (W) times the sulfur content for each component.

$$\%Sulfur_{blend} = \sum W_i(\%Sulfur)_i \quad \text{(B.11)}$$

$$W_i = \frac{V_i \times S.G._i}{\sum V_i \times S.G._i} \quad \text{(B.12)}$$

where:

$\%Sulfur_{blend}$ = percent of sulfur content in total blend

$\%Sulfur_i$ = percent of sulfur content in component i

W_i = weight fraction of component i

V_i = volume fraction of component i

$S.G._i$ = specific gravity of component i

(8) Specific gravity blending (Maples, 2000)

The specific gravity of a blend can be estimated very accurately from the sum of all products of volume fraction (V) times the specific gravity for each component.

$$SG_{blend} = \sum V_i (\%SG)_i \tag{B.13}$$

where:

SG_{blend} = specific gravity of total blend

SG_i = specific gravity of component i

V_i = volume fraction of component i

(9) Pour point blending (Baird, 1989)

Hu and Burns (1970) presented equations for estimating these properties of blends. They employed the concept of substituting blending index values for given properties. Pour point can be determined from the following equation:

$$PPI = 10{,}000 \frac{\left[(PP + 459.69)^{1/x}\right]}{\left[(140 + 459.69)^{1/x}\right]} \tag{B.14}$$

$$PP = \left[(PPI)\frac{(459.69 + 140)^{(1/x)}}{10000}\right]^{x} - 459.69 \tag{B.15}$$

where:

PP = Pour point, °F

PPI = Pour point blending index

x = Constant

Although the optimum value for the constant x must be determined experimentally for a given refinery, Hu and Burns determined that x values of 0.08 for pour points gave the best results on an industry-wide basis.

The pour point of a blend can be estimated very accurately from the sum of all products of volume fraction (V) times the pour point index for each component.

$$PPI_{blend} = \sum V_i (PPI)_i \tag{B.16}$$

where:

PPI_{blend}	=	pour point indices of total blend
PPI_i	=	pour point indices of component i
V_i	=	volume fraction of component i

Table B1 Maurin freeze point blending indices for weight blending (Maurin, 1967)

Freeze Point, °C	Blending Index	Freeze Point, °C	Blending Index	Freeze Point, °C	Blending Index
-50	11.2	-9	28.3	16	65.3
-45	12.2	-8	29.0	17	68.2
-40	14.0	-7	29.8	18	71.0
-35	15.8	-6	30.7	19	74.2
-30	17.6	-5	31.8	20	77.4
-29	17.9	-4	32.9	21	80.7
-28	18.3	-3	34.0	22	83.9
-27	18.7	-2	35.0	23	87.1
-26	19.0	-1	36.1	24	90.4
-25	19.4	0	37.2	25	94.0
-24	19.8	1	38.3	26	97.6
-23	20.3	2	39.5	27	101.4
-22	20.8	3	40.9	28	105.8
-21	21.3	4	42.4	29	110.1
-20	21.8	5	43.8	30	115.4
-19	22.3	6	45.2		
-18	22.9	7	46.7		
-17	23.4	8	48.4		
-16	24.0	9	50.2		
-15	24.5	10	52.0		
-14	25.0	11	54.2		
-13	25.6	12	56.3		
-12	26.2	13	58.5		
-11	26.9	14	60.6		
-10	27.6	15	62.8		

Appendix C Data of commodities and productive units.

Table C1 Fuel used in processing unit (expressed in fuel oil equivalence) (Favennec, 2001)

Units	Fuel used (wt%)
CDU2	1.8
CDU3	1.8
NPU2	2
NPU3	2
ISOU	4
CRU2	2.5
CRU3	2.5
KTU	2
GO-HDS	2
DGO-HDS	2

Table C2 Oman crude specification

API Gravity	34.80		**% Sulfur**	1.160	
Methane	vol%	0.00	Iso-butane	vol%	0.30
Ethane	vol%	0.02	N-butane	vol%	0.92
Propane	vol%	0.33			

Description		**Component Fraction**							
		FG	**LPG**	**LN**	**MN**	**HN**	**IK**	**DO+GO**	**FO**
Vol. yield on crude	lv%	0.02	1.55	5.33	2.70	6.30	13.80	22.40	46.30
Aromatics content	lv%	-	-	1.20	4.25	8.24	11.94	20.94	-
Cetane index		-	-	-	-	30.10	46.40	54.10	-
Freeze point	°C	-	-	-	-85.50	-74.60	-53.50	-8.80	-
RONC		-	-	69.50	49.20	40.60	27.60	-	-
RVP	kg/cm^2	-	-	0.70	0.16	0.04	0.00	-	-
Specific gravity		-	-	0.6517	0.7119	0.7385	0.7844	0.8447	0.9367
Sulfur	wt%	-	-	0.012	0.027	0.030	0.108	0.687	1.938
Viscosity @ 50 °C	cSt	-	-	-	0.41	0.54	1.01	3.64	609.00
Viscosity @ 100 °C	cSt	-	-	-	0.34	0.40	0.62	1.66	52.22
Pour point	°C	-	-	-	-	-	-77.90	-	7.00

Table C3 Tapis crude specification

API Gravity	44.50		**% Sulfur**	0.025	
Methane	vol%	0.00	Iso-butane	vol%	0.82
Ethane	vol%	0.54	N-butane	vol%	1.21
Propane	vol%	0.66			

Description		**Component Fraction**							
		FG	**LPG**	**LN**	**MN**	**HN**	**IK**	**DO+GO**	**FO**
Vol. yield on crude	lv%	0.54	2.69	3.27	5.70	10.70	21.90	30.40	21.50
Aromatics content	lv%	-	-	1.78	5.11	13.09	16.82	17.41	-
Cetane index		-	-	-	-	20.90	45.10	59.30	33.30
Freeze point	°C	-	-	-	-	-83.50	-51.10	6.00	-
RONC		-	-	81.70	76.00	68.20	60.30	-	-
RVP	kg/cm^2	-	-	0.66	0.15	0.05	0.00	-	-
Specific gravity		-	-	0.6713	0.7247	0.7557	0.7857	0.8271	0.9175
Sulfur	wt%	-	-	0.000	0.000	0.001	0.004	0.034	0.056
Viscosity @ 50 °C	cSt	-	-	-	0.43	0.55	0.96	2.88	15.26
Viscosity @ 100 °C	cSt	-	-	-	0.31	0.37	0.58	1.37	4.59
Pour point	°C	-	-	-	-	-	-63.40	-	58.40

Table C4 Labuan crude specification

API Gravity	31.80		**% Sulfur**	0.080	
Methane	vol%	0.00	Iso-butane	vol%	0.18
Ethane	vol%	0.02	N-butane	vol%	0.36
Propane	vol%	0.22			

Description		**Component Fraction (%vol)**							
		FG	**LPG**	**LN**	**MN**	**HN**	**IK**	**DO+GO**	**FO**
Vol. yield on crude	lv%	0.02	0.76	2.42	3.20	9.00	20.30	42.70	20.70
Aromatics content	lv%	-	-	7.05	0.64	16.13	26.36	41.67	-
Cetane index		-	-	-	-	11.30	30.20	39.20	-
Freeze point	°C	-	-	-	-	-	-67.80	-8.10	-
RONC		-	-	83.20	76.40	73.60	50.20	-	-
RVP	kg/cm^2	-	-	0.64	0.16	0.04	0.00	-	-
Specific gravity		-	-	0.6898	0.7402	0.7759	0.8280	0.8911	0.9530
Sulfur	wt%	-	-	0.001	0.001	0.002	0.017	0.083	0.175
Viscosity @ 50 °C	cSt	-	-	-	0.53	0.62	1.04	3.31	132.07
Viscosity @ 100 °C	cSt	-	-	-	0.35	0.41	0.63	1.46	14.50
Pour point	°C	-	-	-	-	-	-86.50	-	45.10

Table C5 Seria light crude specification

API Gravity	35.80		**% Sulfur**	0.068	
Methane	vol%	0.00	Iso-butane	vol%	0.26
Ethane	vol%	0.00	N-butane	vol%	0.62
Propane	vol%	0.25			

Description		**Component Fraction (%vol)**							
		FG	**LPG**	**LN**	**MN**	**HN**	**IK**	**DO+GO**	**FO**
Vol. yield on crude	lv%	0.00	1.13	4.77	4.00	11.30	23.10	35.00	19.50
Aromatics content	lv%	-	-	2.65	8.19	15.88	24.28	53.56	-
Cetane index		-	-	-	-	12.80	31.60	43.00	-
Freeze point	°C	-	-	-	-	-	-59.60	-6.40	-
RONC		-	-	79.50	68.00	60.70	49.60	-	-
RVP	kg/cm^2	-	-	0.69	0.16	0.04	0.00	-	-
Specific gravity		-	-	0.6798	0.7415	0.7696	0.8200	0.8781	0.9506
Sulfur	wt%	-	-	0.000	0.001	0.003	0.020	0.080	0.155
Viscosity @ 50 °C	cSt	-	-	-	0.21	0.21	0.21	0.34	132.96
Viscosity @ 50 °C	cSt	-	-	-	0.21	0.21	0.21	0.27	16.87
Pour point	°C	-	-	-	-	-	-65.80	-	35.90

Table C6 Phet crude specification

API Gravity	40.70		**% Sulfur**	0.050	
Methane	vol%	0.00	Iso-butane	vol%	0.37
Ethane	vol%	0.07	N-butane	vol%	1.04
Propane	vol%	0.37			

Description		**Component Fraction (%vol)**							
		FG	**LPG**	**LN**	**MN**	**HN**	**IK**	**DO+GO**	**FO**
Vol. yield on crude	lv%	0.07	1.78	3.05	3.70	8.50	15.00	28.10	38.00
Aromatics content	lv%	-	-	1.05	5.93	12.15	14.42	14.58	-
Cetane index		-	-	-	-	22.60	45.60	61.40	-
Freeze point	°C	-	-	-	-	-88.80	-48.90	13.40	-
RONC		-	-	70.00	61.40	53.50	41.60	-	-
RVP	kg/cm^2	-	-	0.71	0.16	0.04	0.00	-	-
Specific gravity		-	-	0.6662	0.7200	0.7502	0.7840	0.8236	0.8941
Sulfur	wt%	-	-	0.000	0.000	0.001	0.006	0.047	0.087
Viscosity @ 50 °C	cSt	-	-	-	0.35	0.48	0.94	3.12	39.72
Viscosity @ 50 °C	cSt	-	-	-	0.22	0.26	0.52	1.50	10.59
Pour point	°C	-	-	-	-	-	-51.50	-	55.90

Table C7 Murban crude specification

API Gravity	40.80		**% Sulfur**	0.867	
Methane	vol%	0.00	Iso-butane	vol%	0.45
Ethane	vol%	0.07	N-butane	vol%	1.32
Propane	vol%	0.52			

Description		**Component Fraction (%vol)**							
		FG	**LPG**	**LN**	**MN**	**HN**	**IK**	**DO+GO**	**FO**
Vol. yield on crude	lv%	0.07	2.29	5.94	3.30	10.10	20.40	25.90	29.70
Aromatics content	lv%	-	-	1.76	0.41	12.41	20.48	25.48	-
Cetane index		-	-	-	-	27.90	43.50	53.20	-
Freeze point	°C	-	-	-	-	-90.20	-56.10	-2.60	-
RONC		-	-	76.00	72.20	70.10	56.30	-	-
RVP	kg/cm^2	-	-	0.75	0.16	0.04	0.00	-	-
Specific gravity		-	-	0.6609	0.7145	0.7438	0.7883	0.8455	0.9268
Sulfur	wt%	-	-	0.000	0.000	0.000	0.107	1.051	1.688
Viscosity @ 50 °C	cSt	-	-	-	0.39	0.52	0.93	3.09	88.41
Viscosity @ 50 °C	cSt	-	-	-	0.28	0.35	0.57	1.42	13.84
Pour point	°C	-	-	-	-	-	-73.00	-	33.40

Table C8 Product specifications (x = maximum, n = minimum)

Description		LPG	SUPG	ISOG	JP-1	HSD	FO #1	FO #2	FOVS
RON			91n	95n					
RVP @ 37.8 °C	kPa		62x	62x					
Aromatic Content	vol%		35x	35x	25x				
Freezing Point	°C				-47x				
Cetane Index						47n			
Viscosity @ 50 °C	cSt						7-80	7-180	
Viscosity @ 100 °C	cSt								3-30
Sulfur Content	wt%					0.05x	2x	2x	0.5x
Pour Point	°C						24x	24x	57x

Product specifications are based on rules from Ministry of Commerce (MOC.).

Table C9 Product storage data

Description		LPG	SUPG	ISOG	JP-1	HSD	FO #1	FO #2	FOVS
Product stored at initial	m^3	1,500	14,100	8,400	15,400	54,000	-	-	-
Storage capacity	m^3	5,000	16,000	14,000	28,000	80,000	5,000	15,000	35,000

Appendix D Members of sets.

aref $\in$ {RON, ARO, RVP}

AV_q $\in$ {YD, RON, RVP, ARO, CI, SG}

AW_q $\in$ {FP, S, V50, V100}

C_{CDU} $\in$ {FG, LPG, LN, MN, HN, IK, DO, FO}

C_{CRU} $\in$ {FG, LPG, REF}

CDU $\in$ {CDU2, CDU3}

C_{ia} $\in$ {MTBE, DCC}

C_o $\in$ {OM, TP, LB, SLEB, PHET, MB}

C_p $\in$ {LPG, SUPG, ISOG, JP-1, HSD, FO1, FO2, FOVS}

CRU $\in$ {CRU2, CRU3}

ctank $\in$ {OMT, TPT, LBT, SLEBT, PHETT, MBT}

GSP $\in$ {GSP91, GSP95}

HDS $\in$ {GO-HDS, DGO-HDS}

in $\in$ {MTBE, DCC, REF, ISO, LN, HN}

int $\in$ {MTBET, DCCT, REFT, ISOT, LNT, HNT}

itank $\in$ {MTBET, DCCT}

nap $\in$ {LN, MN, HN}

ptank $\in$ {LPGT, GSP91, GSP95, JPT, DSP, FO1P, FO2P, FOVSP}

UC_u $\in$ {(OM,OMT), (TP,TPT), (LB,LBT), (SLEB,SLEBT), (PHET,PHETT), (MB,MBT)}

UI_u $\in$ {(MTBE,MTBET), (DCC,DCCT)}

UP_u $\in$ {(LPG,LPGT), (SUPG,GSP91), (ISOG,GSP95), (JP-1,JPT), (HSD, DSP), (FO1,FO1P), (FO2,FO2P), (FOVS,FOVSP)}

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