Quantitative Methods for Strategic and Investment Planning in the Oil-Refining Industry

PETROBRAS

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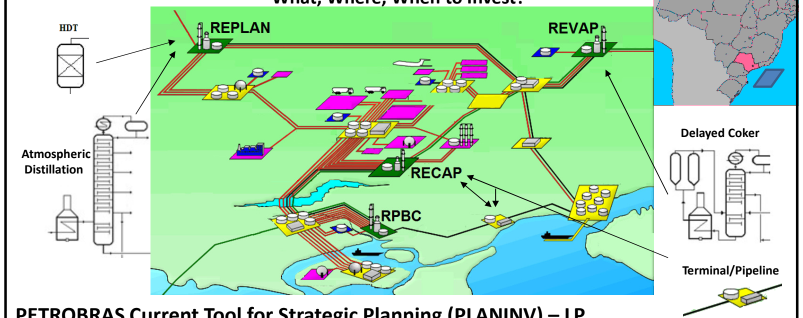
Goal: To develop quantitative methods to predict structural modifications in refining and logistics assets through time

What, Where, When to Invest?



PETROBRAS Current Tool for Strategic Planning (PLANINV) – LP

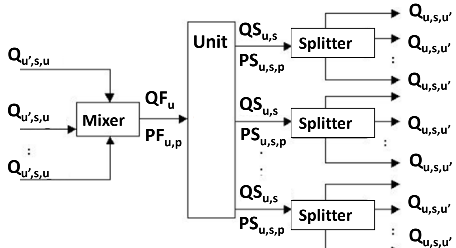
No Production Scenario Synthesis

Only optimize streams transfers (oil and fuels import/export, market supply)

Quantitative Methods →

PLANINV
Scenario Opt (MILP)
+
NLP { Processing, Blending }

Refining Modeling



QF_u Feed Flow
$PF_{u,p}$ Feed Property

$QS_{u,s}$ Product Flow
$PS_{u,s,p}$ Product Property

$Q_{u,s,u'}$ Transfer Stream Flow

u units (tanks, pipelines)
s streams
p properties

(Moro, Zanin & Pinto, 1998)

Mixer:
$$QF_u = \sum Q_{u',s,u}$$

Feed Properties:
$$PF_{u,p} = f(Q_{u',s,u}, PF_{u',s,p})$$

Unit Products:
$$QS_{u,s} = f(QF_u, PF_{u,p}, V_{u,v})$$

Unit Products Properties:
$$PS_{u,s} = f(PF_u, V_{u,v})$$

Splitter:
$$QS_u = \sum Q_{u,s,u'}$$

Mixed-Integer (MILP) + Nonlinear (NLP) Models

ye(R,U,N,T)=expansion of an existent unit
yi(R,U,N,T)= installation of a new unit

QF(R,U,N,T)= operational flow
QC(R,U,N,T)= total capacity
QE(R,U,N,T)= expansion capacity
QI(R,U,N,T)= installation capacity

$$ye_{r,u,n,t}\,QE^L_u \le QE_{r,u,n,t} \le ye_{r,u,n,t}\,QE^U_u$$
$$yi_{r,u,n,t}\,QI^L_u \le QI_{r,u,n,t} \le yi_{r,u,n,t}\,QI^U_u$$

$$QC_{r,u,n,t} = EXCAP_{r,u,n} + QC_{r,u,n,t-1} + QE_{r,u,n,t-1}$$ expansion
$$QC_{r,u,n,t} = QC_{r,u,n,t-1} + QI_{r,u,n,t-1}$$ installation

$$QC_{r,u,n,t} + QE_{r,u,n,t} \le QF_{r,u,n,t+1}$$ expansion
$$QC_{r,u,n,t} + QI_{r,u,n,t} \le QF_{r,u,n,t+1}$$ installation
$$QF_{r,u,n,t} \le QC_{r,u,n,t} \qquad (u,n)_{exp} \wedge (u,n)_{ins}$$ both

INVREF
$QC=QC_{t-1}+Q_{NEW}$ MILP

OPREF
$QF \le QC$ NLP
Crude Diet
Processing
Blending

T1 | T2 | T3 | T

Take an investment decision (binary)

Count on the additional production

Project execution

(R,U,N,T)
R=Refinery
U=Unit type
N=Number of an unit type
T=Time

$$NPV = \sum_T (sales - crude - op.\ costs) - \sum_T invest.\ costs$$

Capital Cost Constraint

$$\sum_R \sum_U \sum_N \begin{pmatrix} \propto_{u,t}{}^E \, QE_{r,u,n,t} + \beta_{u,t}{}^E \, ye_{r,u,n,t} \\ \propto_{u,t}{}^I \, QI_{r,u,n,t} + \beta_{u,t}{}^I \, yi_{r,u,n,t} \end{pmatrix} \le CI(t) \; \forall \; t \quad \text{capital for investment p/ time}$$

Logic Constraints for Expansions and Installations

$$\sum_N (ye_{r,u,n,t} + yi_{r,u,n,t}) \le 1 \;\; \forall \; r,u,t \;\; \text{only one expansion or installation p/ type p/ time}$$

$$\sum_T ye_{r,u,n,t} \le 1 \quad \forall \; r,u,n \qquad \text{expansion can appear only once during all time}$$

$$\sum_T yi_{r,u,n,t} \le 1 \quad \forall \quad r,u,n \qquad \text{installation can appear only once during all time}$$

$$\sum_{U_G} \sum_N (ye_{r,u,n,t} + yi_{r,u,n,t}) \le 1 \forall r,t \;\text{only one expansion or installation p/ group p/ time}$$

Logic Constraints for Unit Type Investments

$$\left[\begin{bmatrix} y_{VDU} \\ \uparrow GO + VR \\ GOC \\ VRC \end{bmatrix} \vee \begin{bmatrix} \neg y_{VDU} \\ \uparrow ATR \\ ATRC, 10\% \text{ in } FCC, DC \end{bmatrix}\right]^{y_{CDU}} \vee \begin{bmatrix} \neg y_{CDU} \\ VRC \end{bmatrix}$$

Unit Groups (U_G):
ATRC = Atmospheric Residue Cracking
GOC = Gasoil Cracking
VRC = Vacuum Residue Cracking
ON= Octane Number Booster

1st Level: $y_{CDU} \vee y_{VRC}$

$$\sum_N (ye_{r,CDU,n,t} + yi_{r,CDU,n,t}) + \sum_{U_{VRC}} \sum_N (ye_{r,u,n,t} + yi_{r,un,t}) \le 1 \qquad \forall \; r,t$$

2nd Level: $y_{CDU} \Rightarrow y_{VDU} \vee y_{ATRC}$ $\qquad \forall \; r,t$

$$\sum_N (ye_{r,VDU,n,t} + yi_{r,VDU,n,t}) + \sum_{U_{ATRC}} \sum_N (ye_{r,u,n,t} + yi_{r,un,t}) \le \sum_N [(ye_{r,CDU,n,t} + yi_{r,CDU,n,t})]$$

$y_{VDU} \Rightarrow y_{GOC} \wedge y_{VRC}$

$$\sum_{U_{GOC}} \sum_N (ye_{r,u,n,t} + yi_{r,un,t}) \le \sum_N [(ye_{r,VDU,n,t} + yi_{r,VDU,n,t})] \qquad \forall \; r,t$$

$$\sum_{U_{VRC}} \sum_N (ye_{r,u,n,t} + yi_{r,un,t}) \le \sum_N [(ye_{r,VDU,n,t} + yi_{r,VDU,n,t})] \qquad \forall \; r,t$$

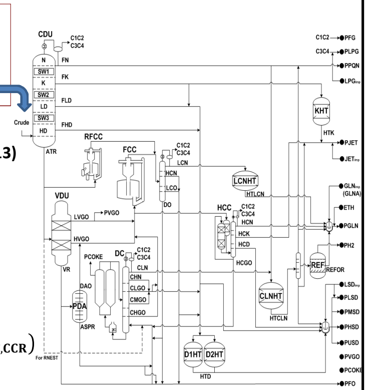
Crude Diet and Processing Equations

Crude diet

$$QF_{CDU} = \sum Q_{CRUDE,CDU}$$

$$PF_{CRUDE,p} = f(Q_{CRUDE,CDU}, PF_{CRUDE,CDU})$$

Crude Assay:
Yields
Gravity
Acidity



Improved Swing-Cut (Menezes, Kelly & Grossmann, 2013)

$$QS_{CDU,s} = \sum Q_{c\wedge sw,s}$$

$$PF_{s,p} = f(Q_{c\wedge sw,s}, PF_{c\wedge sw,p})$$

Other models (Moro, Zanin & Pinto, 1998)

$$QS_{FCC,s} = QF_{FCC}[\overline{Y}_{FCC,s} + \Delta Y_{FCC,s,CCR} \cdot (PF_{FCC,CCR} - \overline{PF}_{FCC,CCR}) + \Delta Y_{FCC,s,RXT} \cdot RXT_{FCC} + \Delta Y_{FCC,s,CFT} \cdot CFT_{FCC}]$$

$$QS_{PDA,ASFR} = QF_{PDA}(1 - EXT_{PDA})$$

$$PS_{HT,s} = PF_{HT}(1 - SEV_{HT})$$

Bilinear Terms

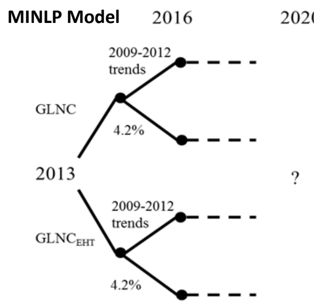
CDU: Crude distillation Unit
FCC: Fluid Catalytic Cracking
PDA: Propane Desasphalting
HT: Hydrotreater

Blending Equations

Property Group	PF or P	base	Property Name	PF or IPF (Property Index)
Concentration	ACID	Mass	Acidity	$PF_{Vol} = \frac{\sum P.Vol}{\sum Vol}$
	GRAV	Vol	Gravity	
	SULF	Mass	Sulfur Content	$PF_{Mass} = \frac{\sum P.GRAV.Vol}{\sum GRAV.Vol}$
	CCR	Mass	Conradson Carbon Residue	
Volatility	DIST	Vol	Distillation	$IP_{RVP} = \left(\frac{1.8P + 32}{549}\right)^{7.8}$
	RVP	Vol (IP)	Reid Vapor Pressure	
	FLASH	Vol (IP)	Flash Point	$IP_{FLASH} = e^{\left(\frac{10006.1}{1.8P+415} - 14.09\right)}$
Combustion	MON	Formula	Motor Octane Number	$PF_{MON} = \sum_i MONB_i.Vol_i$
	RON	Formula	Research Octane Number	
	CETAN	Vol	Cetane Number	
Stability	GUM	Vol	Gum	$IP_{VISC} = \frac{\log_{10} P}{\log_{10} 1000P}$
Fluidity	VISC	Vol (IP)	Viscosity	
	POUR	Vol (IP)	Pour Point	$IPF = \frac{\sum IP.Vol}{\sum Vol}$
	CLOUD	Vol (IP)	Cloud Point	
	PPFC	Vol (IP)	Plug-Flow Filter	$PF = f^{-1}(IPF)$

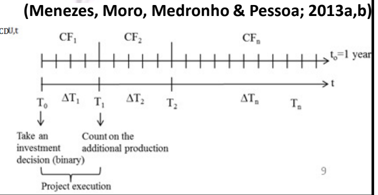
Case 1 – Brazilian Oil-Refining Units Escalation until 2020 (aggregated case for conceptual projects refit – only expansion)

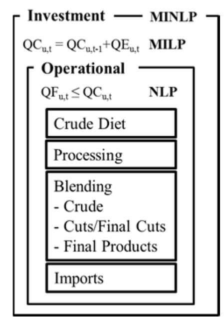
MINLP Model



(Menezes, Moro, Medronho & Pessoa; 2013a,b)

$$NPV = \sum_t \Bigg[(1-tr)0.85F_{t_o} \sum_{t_o} \frac{1}{(1+ir)^{to}} \Bigg(\sum_p pr_{p,t_o} Dem_{p,t} - \sum_{cr} pr_{cr,t_o} \upsilon_{cr,t} QF_{CDU,t}$$
$$- \sum_{imp} pr_{imp,t_o} QF_{imp,t} - 0.5 \sum_{HT} \Upsilon_{HT,t} QF_{HT,t} \Bigg)$$
$$- \frac{1}{(1+ir)^t} \sum_u (\alpha_u QE_{u,t} - \beta_u y_{u,t}) \Bigg]$$





Unit (u)	α_u mi US$/1000m^3	β_u mi US$
CDU	11.7	227.1
VDU	15.1	146.4
FCC	57.5	241.2
HCC	150.6	747.6
RFCC	70.2	588.8
DC	108.9	456.5
KHT	21.8	115.9
DHT	29.6	162.6
LCNHT	14.0	69.3
CLNHT	14.0	69.3
REF	46.0	80.0

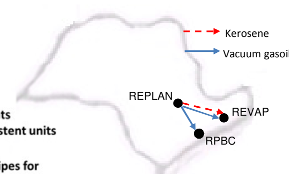
T_1 = 4 years, T_2 = 5 years; Total = 9 years		2016-2020 Investment Porfolio: 2009-2012 trends GLNC	GLNC$_{EHT}$	4.2% p.a. GLNC	GLNC$_{EHT}$
Realized value at moment's decision (mi US$)					
NPV (2016-2025)		8,694.4	4,832.2	9,844.0	4,499.4
Operational Cash (+)	T_1	6,662.5	5,297.2	6,954.1	5,655.1
	T_2	18,904.6	15,522.6	12,524.7	10,302.9
Investment Cash (-)	T_1	16,872.7	15,987.6	9,634.8	11,458.6
Real gain along each investment interval (mi US$)					
Operational Cash (+)	T_1	8,078.4	6,423.0	8,431.9	6,856.9
	T_2	32,413.4	26,614.7	21,474.7	17,665.2
Expansions, QE (K m^3/d) (investments only in T_1)					
CDU		236.2	232.8	140.6	123.1
VDU		53.8	141.5	78.9	81.9
RFCC		89.7		10.1	
FCC		29.4	69.6	38.2	14.4
HCC					21.6
DC			19.1		9.2
KHT		18.1	18.0	9.2	5.3
D2HT		62.3	71.9	47.3	36.9
LCNHT		62.8	38.3	26.3	10.0
CLNHT		15.4	18.0	8.9	8.7
FR3 (no cost related)		15.4	18.0	8.9	8.7
REF		6.1	3.8	2.0	
Investments Costs per unit type (mi US$)					
CDU		2,990.6	2,950.9	1,872.3	1,667.9
VDU		958.4	2,282.9	1,338.1	1,382.6
RFCC		6,882.2		1,301.5	
FCC		1,932.9	4,241.8	2,440.4	1,069.7
HCC					3,993.3
DC			2,536.4		1,458.3
KHT		509.1	506.9	316.7	232.3
D2HT		2,007.5	2,291.6	1,564.1	1,255.6
LCNHT		945.6	603.3	436.5	208.8
CLNHT		283.9	320.7	193.4	190.6
REF		362.5	253.0	172.0	

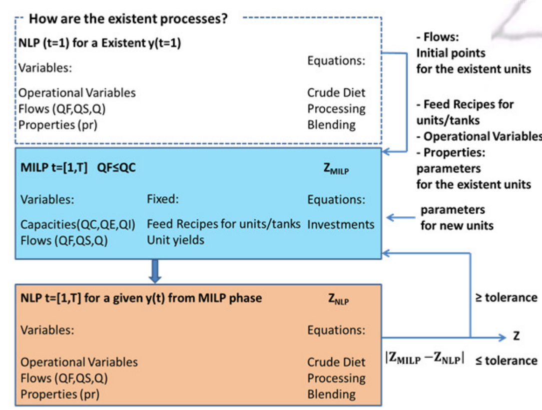
Profit [=] mi US$/day; Margin [=] US$/barrel	2020 results: 2009-2012 trends GLNC T_1	GLNC T_2	GLNC$_{EHT}$ T_1	GLNC$_{EHT}$ T_2	4.2% p.a. GLNC T_1	GLNC T_2	GLNC$_{EHT}$ T_1	GLNC$_{EHT}$ T_2
Realized value at moment's decision								
Profit	4.563	10.359	3.628	8.506	4.763	6.763	3.873	5.645
Margin	1.90	2.62	1.51	2.17	1.99	2.07	1.61	1.76
Real value along each investment interval								
Profit	5.533	17.761	4.399	14.583	5.775	11.767	4.697	9.680
Margin	2.31	4.50	1.83	3.72	2.41	3.54	1.96	3.02
Real value at the investment interval beginning								
Profit	4.983	15.663	3.961	12.860	5.201	10.375	4.229	8.534
Margin	2.16	4.14	1.72	3.41	2.26	3.26	1.84	2.77
Equations	1,117							
Discrete Variables	24							
Continous Variables	1,171							
Non zero elements	3,876							
Non linear elements	1,944							
Iterations	2,265		2,323		2,148		2,303	
CPU (s)	2.81		2.48		2.57		2.50	

Capacity [=] K m^3/d; Unit (u)	2016	2020 (Results): 2009-2012 trends GLNC	GLNC$_{EHT}$	4.2% p.a. GLNC	GLNC$_{EHT}$	2020 (Conceptual Project)
CDU	366	602	599	507	489	536
VDU	155	209	296	234	237	260
RFCC	20	110	20	30	20	20
FCC	72	101	142	110	86	72
HCC	10	10	10	10	32	73
DC	70	70	89	70	79	124
KHT	15	33	33	24	20	15
D2HT	65	127	137	112	102	135
LCNHT	50	113	88	76	60	50
CLNHT	30	45	48	39	39	60
FRAC3	30	45	48	39	39	60
REF	10	16	14	12	10	10
Capital Needed (mi US$)		16,872.7	15,987.6	9,634.8	11,458.6	23,301.9

Case 2 – São Paulo Supply Chain (non-aggregated case for expansion and installation)

MILP + NLP Models Decomposed
Phenomenological Decomposition Heuristics (PDH)





REPLAN	U.N.T	REVAP	U.N.T	RPBC	U.N.T
CDU.(1,2)	CDU.2.2	CDU.1	CDU.2.1	CDU.(1,2,3)	VDU.1.1
VDU.(1,2)	VDU.1.2	VDU.1	VDU.1.1	VDU.(1,2)	FCC.1.1
FCC.(1,2)	FCC.1.1	FCC.1	FCC.1.1	FCC.1	
DC.(1,2)	DHT.2.1	PDA.1		DC.(1,2)	LCNHT.1.1
LCNHT.(1,2)	LCNHT.1.1	DC.1		LCNHT.(1,2)	CLNHT.1.1
CLNHT.(1,2)	CLNHT.1.1	LCNHT.1	LCNHT.1.1	CLNHT.1	DHT.1.1
DHT.(1,2)		CLNHT.1	CLNHT.1.1	DHT.(1,2)	
REF.1	CDU.3.1	KHT.(1,2)	KHT.1.1	REF.1	
	VDU.3.1	DHT.(1,2)	KHT.2.1	ALK.1	
		REF.1	DHT.2.1		
			CDU.3.2		
15 units	6 expans 2 install	12 units	8 expans 1 install	15 units	5 expans

(19 exp / 3 inst)

(R,U,N,T) R.U.(N).T
Refinery
Unit Type
Number of the Unit type
Time

	step	1	2	3	4
CPU (s)	MILP	0.28	0.23	0.17	0.12
	NLP	infeas	infeas	infeas	115.9
NPV (bi U$)	MILP	31.16	31.16	31.16	31.16
	NLP	infeas	infeas	infeas	31.39

MILP

Discrete Var.	Eq.	Var.	Non-zero
444	5,960	7,620	28,693

NLP

Eq.	Var.	Non-zero	Non-Linear
7,223	10,751	70,376	45,446

Next Steps

Structural and temporal decomposition strategies integrated with the phenomenological decomposition heuristics (PDH)

Deal with operational modes to include investments in logistics

Uncertainties?

- **Marketing & Sales (demands)**
- **Purchasing & Procurement**
- **Fuels Prices Brazil x World**
- **Projects delays**