Advances in Conceptual Design Emulation

Peter Kauders, CDE Projects Ltd

A Mathematician's Q&A in the CEGB

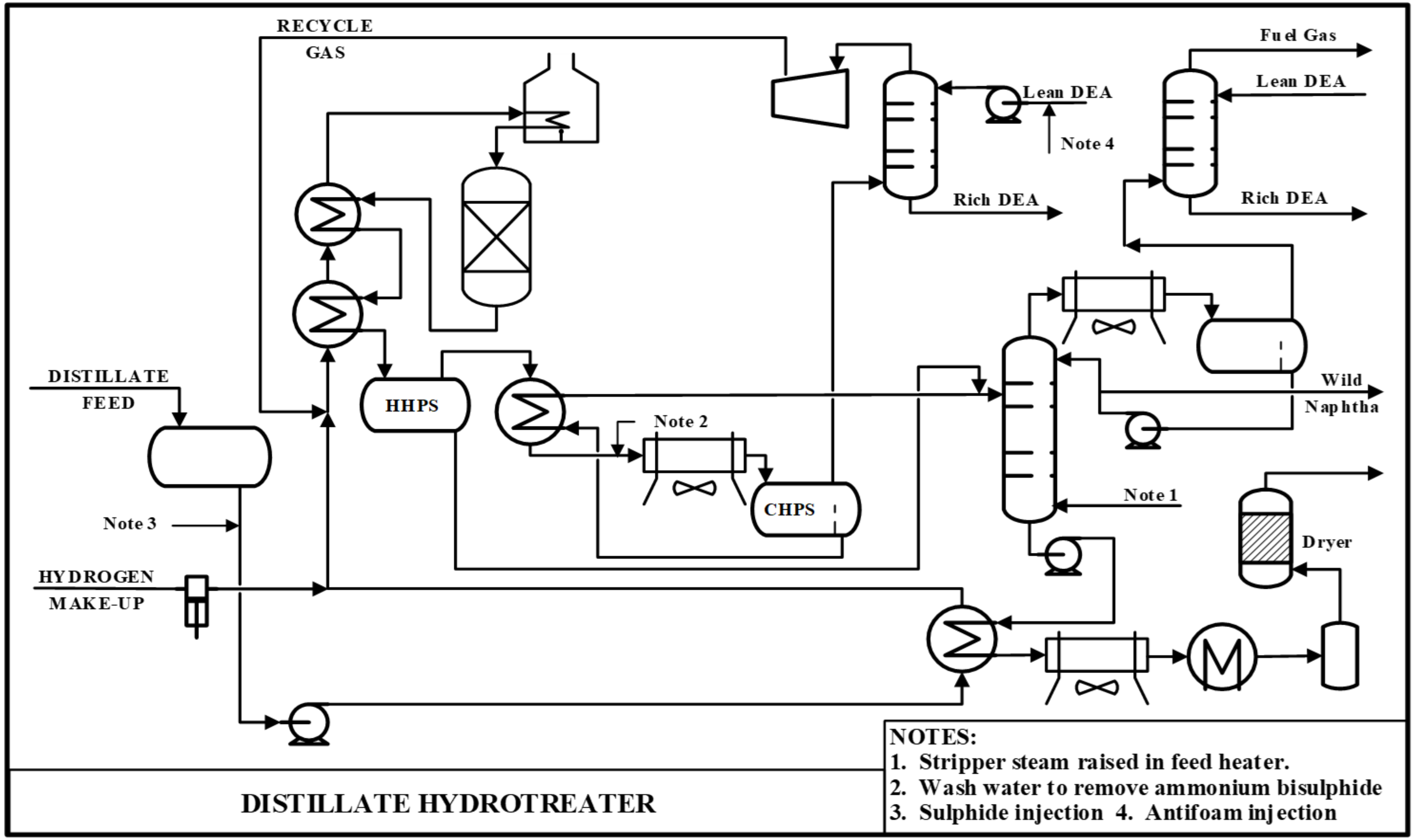
Why do you engineers spend all your time producing those drawings?

What you are doing could be done a lot faster with mathematics!!

Mathematics without producing drawings: *is this the key to speeding up process plant engineering and design?*

Drawings only show the results of our thinking

A PFD is the starting point



Why CDE Started with Cost Estimating – and How

- No drawings produced!
- Equipment duties from stream data used to arrive at equipment costs
- Extensive manual intervention needed, particularly for plant layout
- Logic and mathematics used to arrive at P&ID content
- *But where does the stream data come from?*

Heat and Material Balances before ca.1970

- **Amine unit design starts at the absorber inlet conditions:**
  - amine selection leads to acid gas pickup mole/mole and concentration
  - circulation rate and heat and material balance result

- **Catalyst vendor provides DHT reactor LHSV and H2 partial pressure to meet goals in S, N and aromatics content**

- **Crude and vacuum unit design starts from the feed assay**

Early Studies (with updated 2020 costs)

Hydrotreater capacity, m^3/h	50	100	200	300	400	500
Equipment costs (E)	$7.0m	$10.9	$18.7m	$26.0m	$33.8m	$41.3m
Total materials (%E)	124%	93%	71%	61%	60%	60%
Unit Fixed-capital Investment	$43m	$52m	$71m	$88m	$110m	$129m
Lang factor (calculated)	6.2	4.8	3.8	3.4	3.2	3.1
Cost exponent (incremental, n)	-	0.29	0.43	0.53	0.75	0.77
$K per m^3/h capacity	860	520	355	295	275	255

Gas treating capacity kNm^3/h	50	100	200	300	400	500
Lean amine circulation (m^3/h)	114	227	455	682	909	1136
Equipment costs (E)	$3.4m	$5.0m	$7.9m	$10.6m	$13.4m	$17.0
Total materials (%E)	126%	107%	104%	101%	103%	96%
Unit Fixed-capital Investment	$23m	$29m	$40m	$51m	$63m	$74m
Lang factor (calculated)	6.8	5.8	5.1	4.8	4.7	4.4
Cost exponent (incremental, n)	-	0.31	0.49	0.62	0.68	0.75
$K per m^3/h (amine) capacity	202	129	88	75	69	65

How CDE Developed into Engineering

- Process and mechanical design of equipment e.g. main fractionators
- Heat exchanger thermal design (vital for CDU)
- Steam tables, DEA/MDEA data, physical property correlations
- Operating costs developed alongside capital costs
- Main development difficulties identified

CDE Benchmarking

- Source: Petroleum Refining, Technology and Economics 5th Ed.
- Good fit with both cost curves (indexed) and process technical data
- Gary, Handwerk, Kaiser comment on cost plots:

“Variations in the log-log slope….range from about 0.5 for small-capacity units up to almost 1.0 for very large units…The curvature…..has been described by Chase”

- Linearity in cost curves confirmed in the latest models

CDE Benchmarking of standalone CDU

Crude Distillation Unit capacity, m³/h	200	330	500	750	1000	1500	2000
Gary, Handwerk, Kaiser (2005)	$53m	$64m	$78m	$96m	$111m	$140m	$166m
Escalated to 2020 (Nelson-Farrar**)	$83m	$100m	$122m	$150m	$174m	$219m	$260m
Unit Fixed-capital Investment (model 1)	$88m	$100m	$117m	$141m	$168m	$215m	$262m
Unit Fixed-capital Investment (model 2)	$79m	$91m	$106m	$128m	$150m	$194m	$235m
Cost exponent (incremental, model 1/2)	-	0.27/0.28	0.38/0.38	0.45/0.46	0.63/0.56	0.60/0.62	0.69/0.67

- ***CDE case***
  - ***Power = 0.79 kWh/bbl; FOE = 38 MJ/bbl for model 1***
  - ***Power = 0.76 kWh/bbl; FOE = 34 MJ/bbl for model 2, ME crude***
- ***Gary, Handwerk, Kaiser data is for an integrated CDU (reduced pre-heat)***
  - ***Power = 0.9 kWh/bbl; FOE = 53 MJ/bbl; Feed not stated***

Design Emulation

Design basis

Process design from stream data

Preliminary Engineering with a FEED package

Preliminary MTO and cost estimate

Economic analysis

All possible at the feasibility study stage in just one program

Where does Design Emulation fit best?

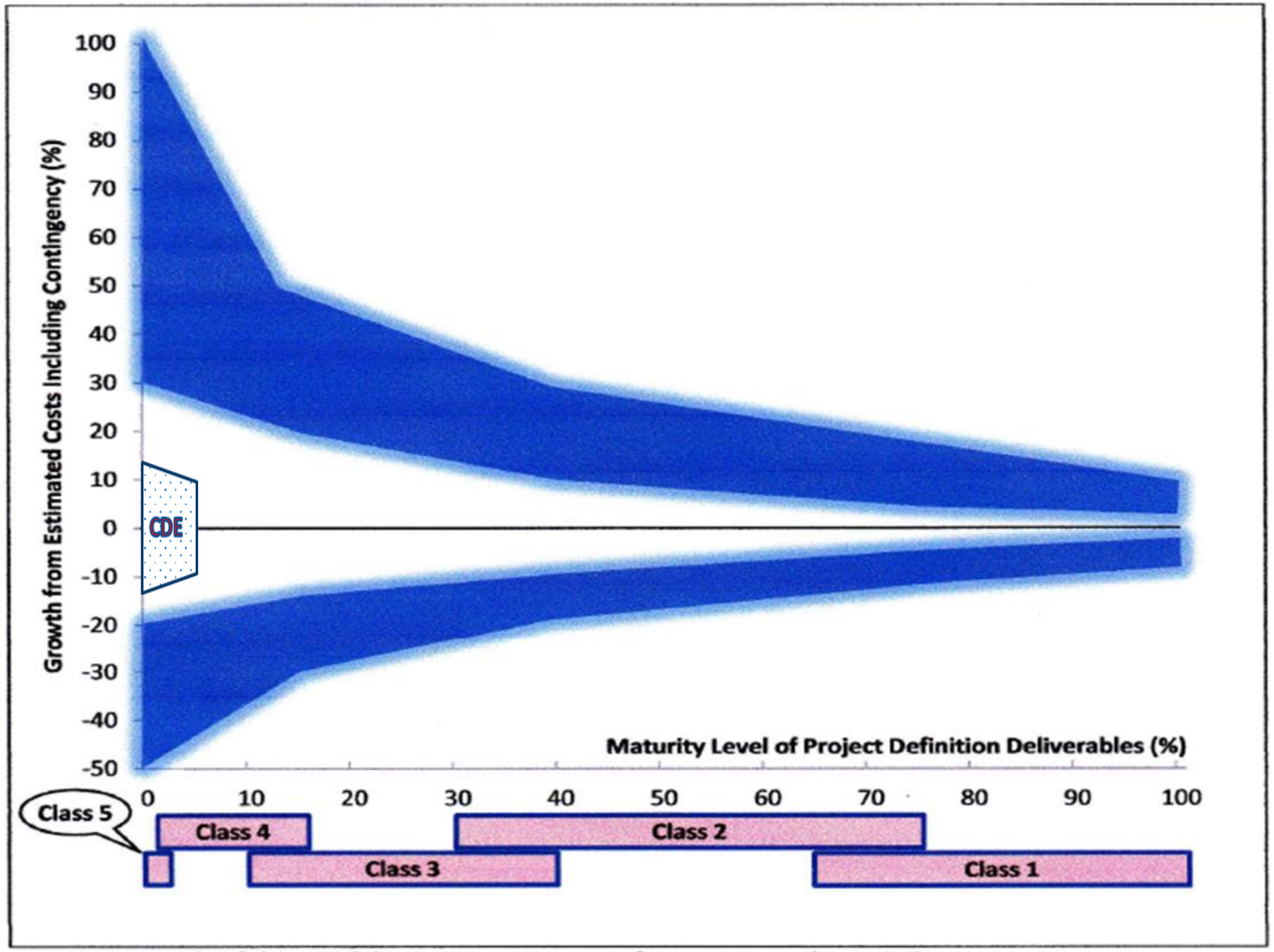


Figure 1 – Example of the Variability in Accuracy Ranges for a Process Industry Estimate

Adapted from AACE International Practice 18R-97

Building a project compass at the feasibility stage

- A means of undertaking meaningful process (licensor) evaluation and value engineering from the study stage onwards
- Accurate equipment design and MTO for cost and change control
- A feasible FEED quality design with extensive documentation
- Accurate layout data for site planning
- CDE aids and expedites, but does not *replace*, engineering

Sample output: Design Basis

Title:	Design Basis				
	Criterion		Value	Units	Notes
A Process					
1	Feed capacity		400	m3/h	
			0.8356	SG	
			334.2	t/h	
2	Feed composition				
		S	20000	ppmw	
		N	1000	ppmw	
		Br no.	0.0		Straight Run Distillate
		P	53.0	%v/v	
		N	34.5	%v/v	
		A	14.4	%v/v	Catalyst supplier to advise %saturation
		TBP	225 - 325	°C	
		VABP	271		
		MeABP	268		
		Kw	11.87		Watson K
			8000	h	Operation
3	Feed conditions	T	40	°C	
		P	5	barg	
4	Product quality				
		S	10	ppmw	
		N	100	ppmw	catalyst supplier advises 90% HDN
5	Performance				
		P_{H2}	50	bar	catalyst supplier advice
		P_T	80	bar	catalyst supplier advice
		LHSV	1.0	h^{-1}	catalyst supplier advice
		Total H_2	44.0	Nm3/m3	Includes soluble H_2
		Chemical H2	36.5	Nm3/m3	calculated/catalyst supplier advice
		Recycle ratio	4	Nm3/Nm3	catalyst supplier advice
		DEA	30	wt%	
B Utilities					
1	LP steam		3.5	barg	
2	Demin water		5.0	barg	
3	CW inlet		35	°C	
4	CW outlet		45	°C	
C Environmental					
		Wet bulb T	32	°C	
		Dry bulb T for aircoolers	40	°C	
		barometric pressure	1.013	bar	
		altitude above sea level	0	m	
D Hydraulic					
		P measured at grade?	Y		for liquid full lines at battery liimits.
		Design margin on T	30	°C	
		Design margin on P	1.05		MOP/OP
			1.10		DP/MOP
		Minimum Design P	3.5	barg	
		Rise to pump shut-off	1.25		times pump differential

Sample output: Material Balance

Stream Name	Flow t/h	Phase	P barg	ToC	ρ kg/m3	Total kgmol/h	MW	Cp	SG	Servic	dyn. vis.	k	Ppc bar	Tpc (K)	w	kgmol/h H_2S	H_2	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	LN	MN	HN	Kero	LGO	C_{6+}	DEA
combined feed	370.4	L/V	91	223	166.1	5597.1	66.17	3.188	0.836	HC	0.01	0.1	16.91	731.0	0.5706	0.0	2638.8	973.6	211.5	117.9	62.5	0.00	0.00	0.00	0.079	0.020	0.00	0.001	1592.8	1592.9	
combined feed liquid	334.2	L	91	223	691.8	1592.8	209.84	2.802	0.836	HC	0.40	0.12	16.91	731.0	0.5706	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1592.8	1592.8	
combined feed vapour	36.1	V	91	223	20.1	4004.3	9.03	6.371		HR	0.01	0.05	24.24	101.6	-0.1256	0.0	2638.8	973.6	211.5	117.9	62.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	
pre-heated feed	370.4	L/V	89	360	129.6	5597.1	66.17	3.616	0.836	HC	0.01	0.10	16.91	731.0	0.5706	0.0	2638.8	973.6	211.5	117.9	62.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1592.8	1592.9	
pre-heated feed liquid	296.3	L	89	360	593.3	1562.1	189.71	3.382	0.836	HC	0.17	0.11	16.91	731.0	0.5706	0.0	120.9	16.1	6.8	6.9	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1405.8	1405.8	
pre-heated feed vapou	74.0	V	89	360	31.4	4035.1	18.35	4.091		HR	0.01	0.05	24.06	131.2	-0.0925	0.0	2517.9	957.5	204.7	111.0	56.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	187.0	187.1	
reactor inlet	370.4	L/V	85	380	119.6	5597.1	66.17	3.720	0.836	HC	0.01	0.10	16.91	731.0	0.5706	0.0	2638.8	973.6	211.5	117.9	62.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1592.8	1592.9	
reactor inlet liquid	277.8	L	85	380	578.6	1451.4	191.38	3.468	0.836	HC	0.15	0.11	16.91	731.0	0.5706	0.0	104.4	13.3	5.4	5.4	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1318.6	1318.6	
reactor inlet vapour	92.6	V	85	380	35.4	4145.7	22.34	3.977		HR	0.01	0.05	23.90	143.7	-0.0787	0.0	2534.4	960.4	206.1	112.5	58.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	274.2	274.3	
reactor effluent	371.5	L/V	80	405	114.0	5340.1	69.57	3.823	0.829	HC	0.01	0.10	17.49	719.5	0.5493	208.4	2003.0	1025.8	239.3	155.8	105.6	0.0	0.0	0.0	8.5	13.7	0.0	10.2	1569.8	1602.2	
reactor effluent liquid	239.1	L	80	405	552.0	1269.2	188.42	3.588	0.829	HC	0.13	0.11	17.49	719.5	0.5493	4.0	66.5	11.1	4.7	5.3	5.4	0.0	0.0	0.0	1.1	3.3	0.0	5.0	1162.8	1172.1	
reactor effluent vapou	132.4	V	80	405	46.9	4070.9	32.52	3.679		HR	0.01	0.05	29.36	199.7	-0.0189	204.4	1936.5	1014.7	234.6	150.5	100.2	0.0	0.0	0.0	7.4	10.4	0.0	5.3	407.0	430.1	
hot reactor effluent	371.5	L/V	80	405	114.0	5340.1	69.57	3.823	0.829	HC	0.01	0.10	17.49	719.5	0.5493	208.4	2003.0	1025.8	239.3	155.8	105.6	0.0	0.0	0.0	8.5	13.7	0.0	10.2	1569.8	1602.2	
reactor effluent to HHI	371.5	L/V	78	273	145.5	5340.1	69.57	3.167	0.829	HC	0.01	0.10	17.49	719.5	0.5493	208.4	2003.0	1025.8	239.3	155.8	105.6	0.0	0.0	0.0	8.5	13.7	0.0	10.2	1569.8	1602.2	
warm reactor effluent l	317.7	L	78	273	647.4	1741.1	182.50	3.027	0.829	HC	0.26	0.12	17.49	719.5	0.5493	12.7	103.7	24.0	13.0	16.8	18.1	0.0	0.0	0.0	3.8	9.3	0.0	9.2	1530.5	1552.7	
warm reactor effluent v	53.8	V	78	273	26.1	3599.0	14.94	3.801		HR	0.01	0.05	30.49	143.8	-0.0804	195.7	1899.2	1001.8	226.3	139.0	87.5	0.0	0.0	0.0	4.7	4.4	0.0	1.0	39.3	49.5	
cold reactor effluent	54.0	L/V	77	55	44.0	3599.0	15.01	3.610	0.829	HC	0.01	0.10	17.49	719.5	0.5493	195.7	1899.2	1001.8	226.3	139.0	87.5	0.0	0.0	0.0	4.7	4.4	0.0	1.0	39.3	49.5	
CHPS liquid	12.2	L	77	55	805.0	125.3	97.63	2.100	0.829	HC	2.53	0.14	17.49	719.5	0.5493	12.8	9.0	6.2	8.3	17.5	23.1	0.0	0.0	0.0	3.8	4.3	0.0	1.0	39.3	48.4	
CHPS vapour	41.8	V	77	55	34.5	3473.7	12.03	2.044		HR	0.01	0.05	30.31	132.2	-0.0927	182.8	1890.2	995.6	218.0	121.5	64.4	0.0	0.0	0.0	0.9	0.2	0.0	0.0	0.0	1.1	
CLPS inlet	12.2	L/V	7	55	59.7	125.3	97.63	2.170	0.829	HC	0.01	0.10	17.49	719.5	0.5493	12.8	9.0	6.2	8.3	17.5	23.1	0.0	0.0	0.0	3.8	4.3	0.0	1.0	39.3	48.4	
CLPS liquid	10.3	L	7	55	800.8	68.9	149.79	2.100	0.829	HC	2.53	0.14	17.49	719.5	0.5493	2.3	0.1	0.1	0.9	5.4	12.1	0.0	0.0	0.0	3.5	4.2	0.0	1.0	39.3	48.0	
CLPS vapour	1.9	V	7	55	9.9	56.3	33.83	1.873		HC	0.01	0.05	46.69	298.1	0.0705	10.5	8.9	6.1	7.4	12.1	11.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.3	

Sample output: Sized Equipment List

Full Tag	Title	Type	P1	Shell Pd	Shell Td	Tube Pd	Tube Td	Metallurgy	Rated	Units	Motor	D	H	L	Item	Total
			barg	barg	oC	barg	oC				kW	m	m	m	t	$K
F-01A/C	HDT Feed Filter	cartridge	4.3	6.3	50			CS	34	m2		1.3	1.5		3	155
V-01	HDT Feed Surge Drum	gravity	5	6.3	70			CS	62	m3		2.8		11.2	12.8	157
V-02	Sulphide Drum	gravity	0	3.5	70			CS	7	m3		1.4		5.6	3	42
P-02A/B	Sulphide Pump	metering	5.4	6.7	70			CS	6	l/m	0.4			2	0	8
P-01A/B	HDT Feed Pump	centrifugal	111.5	137.7	70			CS	450	m3/h	1865			2	37	2099
E-01	HDT Feed/Effluent Exchanger	S&T	85.9	137.7	390	92.7	435	SS347	1535	m2		0.7		6.1	136	2925
K-21A/B	H-01 ID Fan	fan	0.1	atmos	235			CS	24847	m3/h	29.9		0	2	1	123
E-21	H-01 Air Preheater	convection	0.1	atmos	377	atmos	490	CS	153	m2			0.3	9.6	28	272
K-22A/B	H-01 FD Fan	fan	0.1	atmos	70			CS	14868	m3/h	18.7		0	2	0	91
H-01	Feed Heater	cabin	85.4	137.7	440			SS347	9.8	MW			4.8	9.6	46	2644
H-02	H-01 Feed Preheater	convection bank	85.5	137.7	410			SS430	3.9	MW			0.9	9.6	18	
Z-01	H-01 Stack				460			CS, refractory lir	38123	m3/h		0.7	4.8		0.8	
H-03	H-01 Steam Superheater	convection bank	11.9	15.9	382			CS	1.1	MW			0.2	9.6	2	
	H-01 Transfer Line															
R-01	HDT Reactor		80.7	98.2	435			1.25Cr, SS clad	440	m3		4.9	30		681	7363
V-12	Hot HP Separator	mesh pad	78.3	90.4	303			1.25Cr, SS clad	37	m3		2.3		9.2	57	756
E-03	Product Trim Cooler	S&T	6.7	16.9	85	7.3	75	CS	875	m2		1.1		6.1	24	257
F-11A/B	Product Coalescer	coalescer	6.1	16.9	50			CS	2	m2		1.4		2.8	4	110
D-11A/B	Product Drier	salt	5.3	16.9	70			CS	15	m2		4.4	8.5		54	1063
Y-01	Anti-foam Dosing Skid		0	3.5	70			SS316	0.10	m3/h		0	0	2	1	72
T-21	Y-01 Anti-foam Tank	rectangular		atmos	70			SS316	2.3	m3		1.5			1	
P-21A/B	Y-01 Anti-foam Dosing Pump	metering		3.5	70			SS316	0.30	l/m	0.4			2	0	
S-01	Open Drains Sump	rectangular	0	atmos	50			concrete	5	m3		0	-1.4	2.4	0	
P-24	Open Drains Pump	sump	7.6	9.3	50			CS	11	m3/h	7.5			2	0	29
P-25	Stormwater Pump	sump	5.9	7.3	50			CS	55	m3/h	18.7			2	0	48

Sample output: piping and valve quantities

Pipe Report (m)			Sch	84	30	24	20	18	16	14	12	10	8	6	4	3	2	1.5	1	0.75	Material gro
Seamless	1.1	CS	20		17	184		28		54		522	429								
			30																		
			40										26	1149	496	491	942				
			60																		
			80S																		
			80								21	170	212	42	210	130	689	1960			
			100																		
			120							32	54	159	21		42						
			160														684		10		
			XXS																		8775

Valve Report			Class	84	30	24	20	18	16	14	12	10	8	6	4	3	2	1.5	1	0.75	Material group total
Block	1.1	CS	1			3		2				15	19	40	29	32	114	61	102	540	
			3										1	6			208	1	7	54	
			6									2	7		9	5	94		36	202	
			9								1	3		4	21	7	20		14	72	
	1.7	CrMo	1									3	2	7			1		2	12	
			3									4		1	5	2	4		4	30	
			6									2			2		1			14	
			9																		
	2.2	SS316	1											4	2	15	12	8	10	84	
			3												4	2	18				
			6											2	5	4	10	4	8	32	
			9							2		4				5	33	2	22	72	
	Sub-total					3		2		2	1	33	29	64	77	72	515	76	205	1112	2191
Globe	1.1	CS	1												2	3	5	7			
			3																		
			6										4	2	1	2	1				
			9																2		
	1.7	CrMo	1																		
			3													2					
			6												1						
			9																		
	2.2	SS316	1													2	1	1			
			3																		
			6													1		1			
			9																		
	Sub-total												4	2	4	10	7	9	2		38
Check	1.1	CS	1			2		2							1		9	6			
			3																		
			6									1	3		3		3				
			9									3									
	1.7	CrMo	1																		
			3									3		1							
			6																		
			9																		
	2.2	SS316	1													3		1			
			3																		
			6												3	3					
			9																		
	Sub-total					2		2				7	3	1	7	6	12	7			47
	Total																				2276

Sample output: cable summary

Cable Report (m)													
	mm2	**1.5**	**2.5**	**4**	**10**	**16**	**25**	**35**	**70**	**95**	**240**	**400**	**Total (m)**
	Cores												
HT	**3**								1178	432	370		1980
LT	**3**	3372	422	924	2925	1050	877	582		502			10654
LC	**3**	3538	4400										7938
Total		6910	4822	924	2925	1050	877	582	1178	934	370	0	**20572**

Advanced CDE Model vs. Traditional Engineering

Item	Engineering, MTO, Cost	Advanced CDE
Project kick off: weeks	Assembling Team	Model Building
Execution time	Months – 12+?	Minutes
Order of work	Complex: Many Tasks	One program
Ability to change basis	Limited as job progresses	Totally flexible

Advanced CDE Model vs. Traditional Engineering

Item	Engineering, MTO	Advanced CDE
Deliverables	Sequential	Fully Interactive
Planning, progress	Full time job!	Not required
Change control	Time consuming for all	Automatic (quantities, costs)
Drawings/3D	Essential	Not required/xyz determined

Advanced CDE Model vs. Traditional Engineering

Item	Engineering, MTO, Cost	Advanced CDE
Design risk	Adds 10% to project cost?	Minimal
Optimisation	Time consuming and uncertain	Easy and accurate
Layout	Takes weeks/months to develop	Program report
PR loads, I/O	Take 6 months+ to begin work	Immediate

Process Plant Design Emulation (PPDE)

- Optimisation improved by fast engineering, MTO and cost estimating
- Design sequence unimportant - no need for planning or expediting
- No need for offshoring - project can be done in one country/time zone
- CDE now at the point of integrating process simulation: patents pending for PPDE (advanced CDE)

Contact:
pkauders@cdeprojects.com