Process Control Forum 2013

CONQUERING CHALLENGES FOR SUSTAINABLE EXCELLENCE

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Process Control Forum 2013

TAGUCHI METHOD FOR CONDENSATE FRACTIONATION UNIT (CFU)

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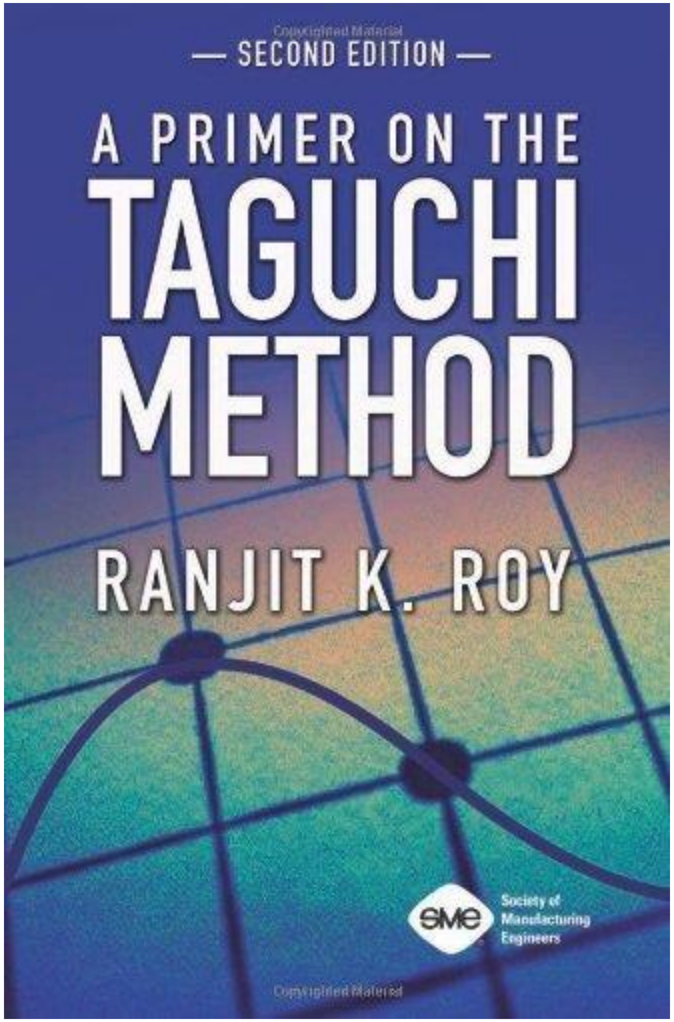
Introduction of Taguchi's Parametric Design



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— SECOND EDITION —

A PRIMER ON THE TAGUCHI METHOD

RANJIT K. ROY

SME Society of Manufacturing Engineers

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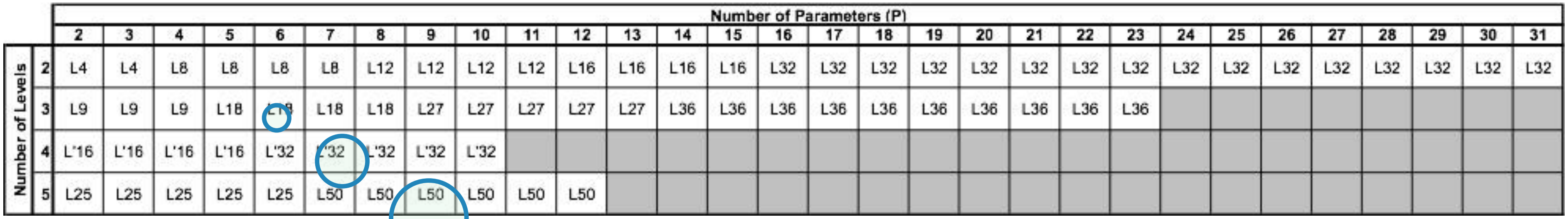
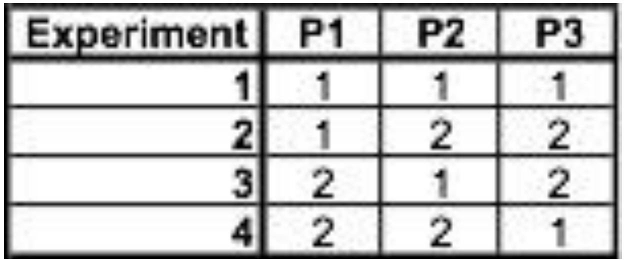
- ✓ A powerful statistical technique to optimize the process design problems
- ✓ Reduces process variation through robust design of experiments (DOE).
- ✓ Provides alternative solution where the conventional factorial design is simplified in a cost and time efficient way
- ✓ Establishment of unbiased experiments through the balanced characteristic of Orthogonal Arrays (OA)

Orthogonal Array Selection



Number of Levels	Number of Parameters (P)																													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

Number of Levels		Number of Factors								
		2	3	4	5	6	7	8	9	10
	2	L4	L4	L8	L8	L8	L8	L12	L12	L12
	3	L9	L9	L9	L18	L18	L18	L18	L27	L27
	4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32
	5	L25	L25	L25	L25	L25	L50	L50	L50	L50

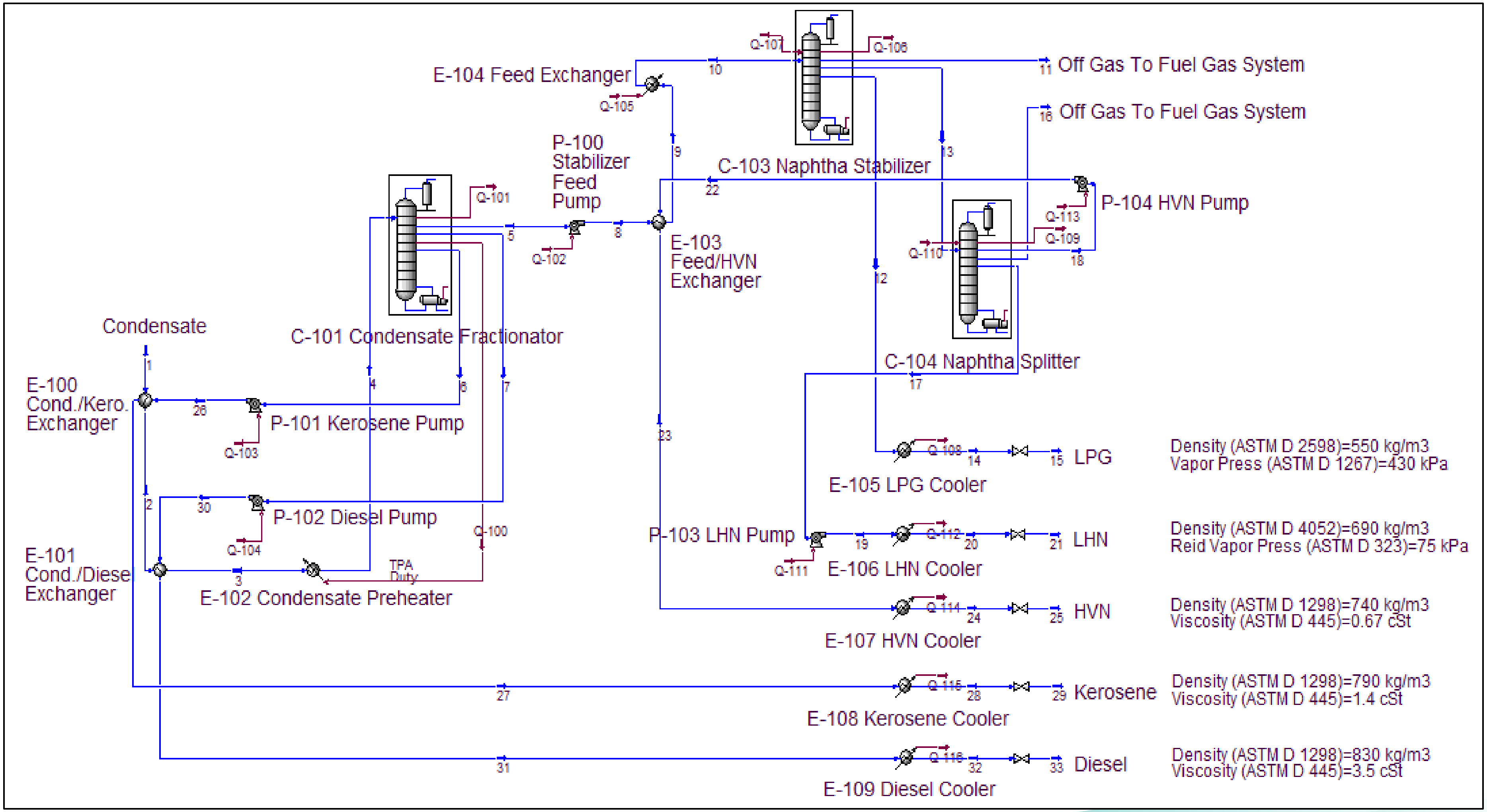


Experiment	P1	P2	P3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

Notes:

1. Arrays are designed to allow all parameters to vary twice at Levels 1 and 2 (unbiased experiments).
2. Need to run only 4 instead of 27 (3^3) experiments.

Process Flow Diagram of CFU



Model Validation: Comparison of Operating Parameters

Unit	No. of Tray	Main Product Stream	Parameter	HYSYS	Actual	Deviation (%)
C-101 Condensate Fractionator	32	S30 Diesel to storage	Flow Rate (kg/h)	34801.1	35356.0	-1.6
			Temperature (°C)	60.5	60.0	0.8
			Pressure (kPa)	156.9	160.0	-1.9
C-102 Kerosene Stripper	22	S29 Kerosene to storage	Flow Rate (kg/h)	24709.9	23662.0	4.4
			Temperature (°C)	60.2	60.0	0.3
			Pressure (kPa)	706.1	720.0	-1.9
C-103 Naphtha Stabilizer	65	S15 LPG to storage	Flow Rate (kg/h)	16835.4	17601.0	-4.3
			Temperature (°C)	40.2	40.0	0.5
			Pressure (kPa)	1177.0	1200.0	-1.9
C-104 Naphtha Splitter	74	S21 LHN to storage	Flow Rate (kg/h)	162483.3	159006.0	2.2
			Temperature (°C)	40.2	40.0	0.4
			Pressure (kPa)	255.0	260.0	-1.9
		S25 HVN to storage	Flow Rate (kg/h)	107639.3	108461.0	-0.8
			Temperature (°C)	75.2	75.0	0.3
			Pressure (kPa)	480.5	490.0	-1.9

Model Validation: Comparison of Products Specifications based on ASTM Standard

Product	Specification	Value	HYSYS
LPG	Density at 15 °C, Kg/m^3 (ASTM D 2598)	560 (max)	553.85
	Vapor Pressure at 37.8 °C, kPa (ASTM D 1267)	380-830 (max)	433.33
LHN	Density at 15 °C, Kg/m^3 (ASTM D 1298 or ASTM D 4052)	660-730 (max)	690.18
	Reid Vapor Pressure at 37.8 °C, kPa (ASTM D 323)	94.5 (max)	75.55
HVN	Density at 15 °C, Kg/m^3 (ASTM D 1298)	755 (max)	741.54
	Viscosity at 40 °C, cSt (ASTM D 445)	0.55 - 1.04	0.6713
Kerosene	Density at 15 °C, Kg/m^3 (ASTM D 1298)	775-839 (max)	788.78
	Viscosity at 40 °C, cSt (ASTM D 445)	1 - 2 (max)	1.3921
Diesel	Density at 15 °C, Kg/m^3 (ASTM D 1298 or ASTM D 4052)	820-845 (max)	831.50
	Viscosity at 40 °C, cSt (ASTM D 445)	2 - 4.5 (max)	3.4799

Problem Statements and Objective

Problem Statement

- Fluctuation of market price of condensate feedstock and its products
- Time-varying nature of condensate feedstock flow rates
- Challenges in determining the significant decision variables for effective implementation of optimization strategy

Objective

- To systematically determine the significant decision variables for profit optimization of CFU using Taguchi method

Implementation of Taguchi Method

Step 1

Problem Formulation

- Objective Function
- 9 Controllable Factors
- 2 Noise Factors
- 3-Levels each [low, medium, high]

Step 2

Experimental Design

Orthogonal Design:

- Controllable Factors L_{27} (3^9) internal array
- Noise Factors L_9 (3^2) external array

Step 3

Analysis of Results

- Signal-to-Noise Ratio (SNR)
- Analysis of Means (ANOM)
- Analysis of Variance (ANOVA)
- Response Plot

Description of Objective Function, Factors and Levels

Objective function: To achieve the highest profit by selecting the most significant operating parameters (controllable and noise factors) at their optimal configuration.

$$P = \sum_{i=1}^{I} R_i - C_{Feed} - C_{Utilities}$$

P : *Profit*
R_i : *Revenues*
C_{Feed} : *Cost of condensate*
$C_{Utilities}$: *Operational expenses*

Factors	Level 1	Level 2	Level 3	Units	Description
A	122	124	126	°C	C-101 Stage 28 Temperature
B	304	306	308	°C	C-101 Bottom Stage Temperature
C	23139	25710	28281	Kg/hr	C-102 Kerosene Prod. Flow Rate
D	288900	321000	353100	Kg/hr	C-101 Top Pump-Around Flow Rate
E	83	84	85	°C	C-103 Top Stage Temperature
F	1137	1177	1217	kPa	C-103 Top Stage Pressure
G	150.4	151.4	152.4	°C	C-104 Bottom Stage Temperature
H	80.07	81.07	82.07	°C	C-104 Top Stage Temperature
I	103.4	106.4	109.4	kPa	C-104 Top Stage Pressure
J	330338	347724	365110	Kg/hr	Condensate Flow Rate
K	2.42	2.49	2.56	RM/kg	Condensate Price

Controllable Factors

Noise Factors

Taguchi Orthogonal Arrays

Runs	Factors								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
1	2	3	1	2	2	3	1	1	2
2	2	1	2	3	1	2	3	1	2
3	1	1	1	1	2	2	2	2	2
4	3	3	2	1	2	1	3	1	3
5	2	3	1	2	3	1	2	2	3
6	3	2	1	3	2	1	3	3	2
7	2	2	3	1	1	2	3	2	3
8	2	1	2	3	3	1	2	3	1
9	1	1	1	1	1	1	1	1	1
10	3	2	1	3	1	3	2	2	1
11	3	3	2	1	1	3	2	3	2
12	3	3	2	1	3	2	1	2	1
13	1	2	2	2	3	3	3	1	1
14	1	2	2	2	1	1	1	2	2
15	2	1	2	3	2	3	1	2	3
16	1	3	3	3	2	2	2	1	1
17	3	1	3	2	3	2	1	3	2
18	3	1	3	2	1	3	2	1	3
19	2	2	3	1	2	3	1	3	1
20	3	1	3	2	2	1	3	2	1
21	1	3	3	3	1	1	1	3	3
22	1	3	3	3	3	3	3	2	2
23	2	2	3	1	3	1	2	1	2
24	3	2	1	3	3	2	1	1	3
25	2	3	1	2	1	2	3	3	1
26	1	2	2	2	2	2	2	3	3
27	1	1	1	1	3	3	3	3	3

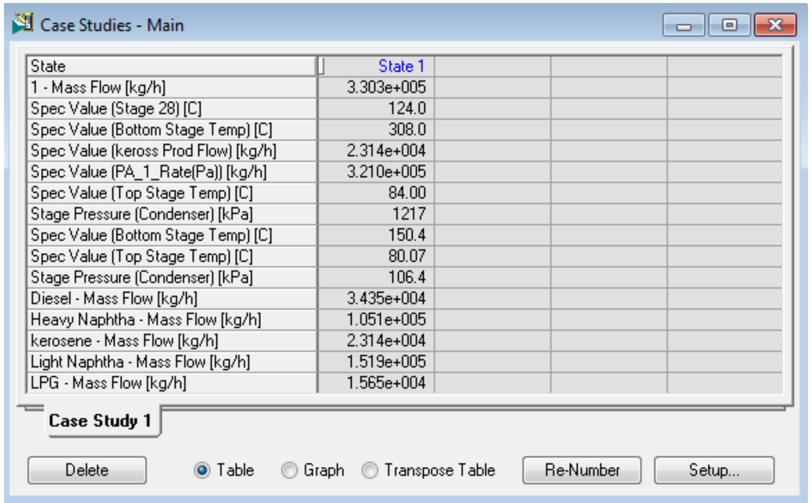
L_{27} (3^9) internal array

Cases	Factors	
	J	**K**
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

L_9 (3^2) external array

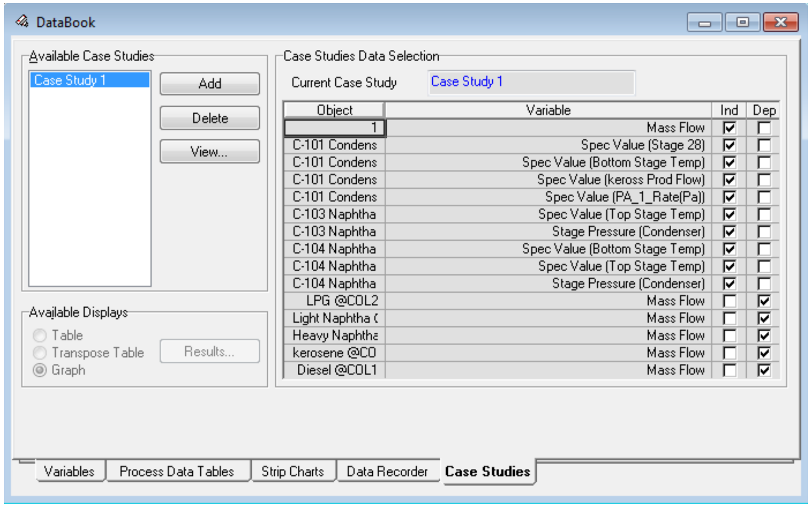
HYSYS DataBook Case Study

Selection of both the independent and dependent variables for the HYSYS simulations based on the cross-orthogonal arrays design.



State	State 1
1 - Mass Flow [kg/h]	3.303e+005
Spec Value (Stage 28) [C]	124.0
Spec Value (Bottom Stage Temp) [C]	308.0
Spec Value (keross Prod Flow) [kg/h]	2.314e+004
Spec Value (PA_1_Rate(Pa)) [kg/h]	3.210e+005
Spec Value (Top Stage Temp) [C]	84.00
Stage Pressure (Condenser) [kPa]	1217
Spec Value (Bottom Stage Temp) [C]	150.4
Spec Value (Top Stage Temp) [C]	80.07
Stage Pressure (Condenser) [kPa]	106.4
Diesel - Mass Flow [kg/h]	3.435e+004
Heavy Naphtha - Mass Flow [kg/h]	1.051e+005
kerosene - Mass Flow [kg/h]	2.314e+004
Light Naphtha - Mass Flow [kg/h]	1.519e+005
LPG - Mass Flow [kg/h]	1.565e+004

● Table ○ Graph ○ Transpose Table



○ Table ○ Transpose Table ● Graph

Case Studies Data Selection

Current Case Study: Case Study 1

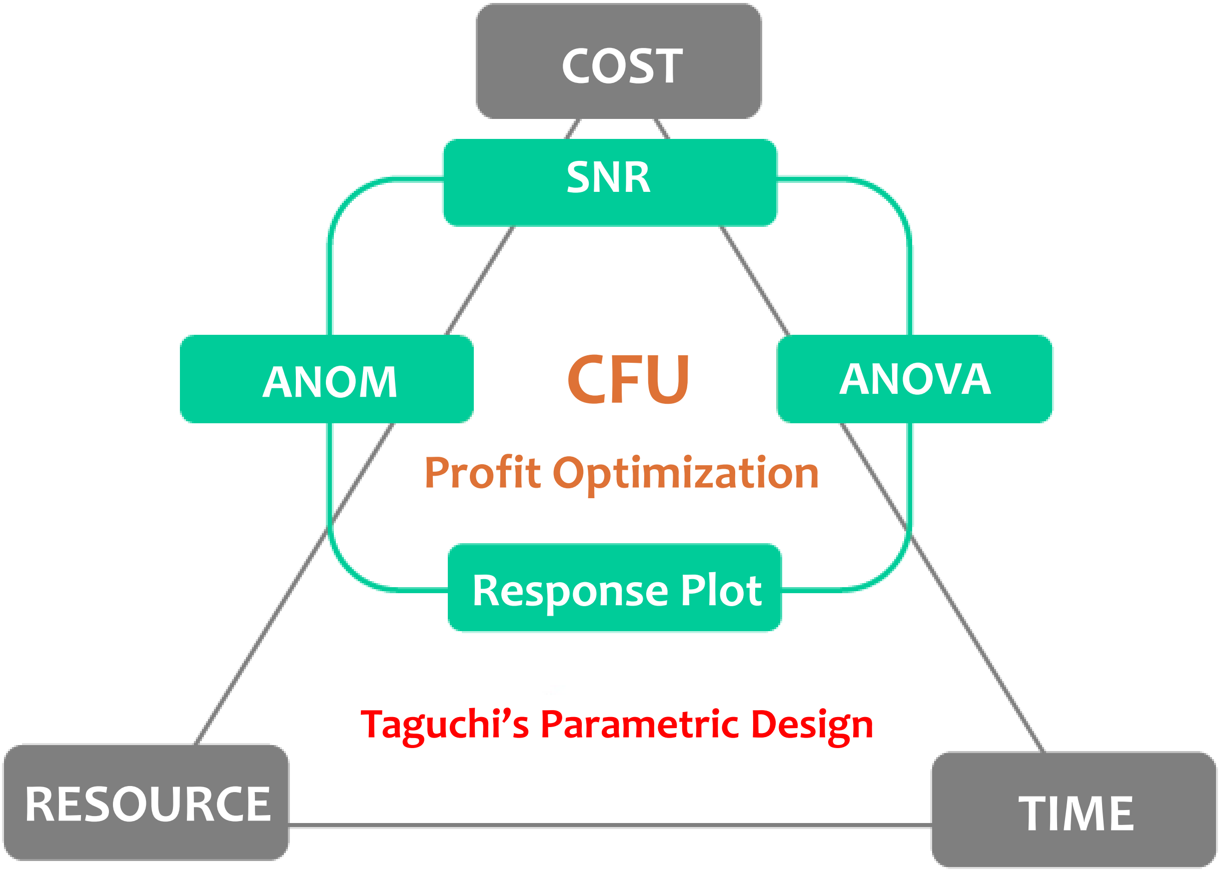
Object	Variable	Ind	Dep
1	Mass Flow	☑	☐
C-101 Condens	Spec Value (Stage 28)	☑	☐
C-101 Condens	Spec Value (Bottom Stage Temp)	☑	☐
C-101 Condens	Spec Value (keross Prod Flow)	☑	☐
C-101 Condens	Spec Value (PA_1_Rate(Pa))	☑	☐
C-103 Naphtha	Spec Value (Top Stage Temp)	☑	☐
C-103 Naphtha	Stage Pressure (Condenser)	☑	☐
C-104 Naphtha	Spec Value (Bottom Stage Temp)	☑	☐
C-104 Naphtha	Spec Value (Top Stage Temp)	☑	☐
C-104 Naphtha	Stage Pressure (Condenser)	☑	☐
LPG @COL2	Mass Flow	☐	☑
Light Naphtha (	Mass Flow	☐	☑
Heavy Naphtha	Mass Flow	☐	☑
kerosene @CO	Mass Flow	☐	☑
Diesel @COL1	Mass Flow	☐	☑

Results of Cross-Orthogonal Array Experiments

Runs	Profits (RM '000/hour)									
	x^{1n}	x^{2n}	x^{3n}	x^{4n}	x^{5n}	x^{6n}	x^{7n}	x^{8n}	x^{9n}	$\bar{x}^{n}$
1	109.12	85.99	62.87	114.26	89.92	65.58	119.41	93.86	68.30	89.92
2	109.01	85.88	62.76	114.10	89.76	65.42	119.20	93.65	68.09	89.76
3	110.76	87.64	64.51	115.96	91.62	67.28	121.17	95.61	70.05	91.62
4	106.93	83.80	60.68	111.92	87.58	63.24	116.92	91.36	65.80	87.58
5	108.73	85.60	62.48	113.86	89.52	65.18	118.99	93.43	67.87	89.52
6	107.40	84.27	61.15	112.50	88.16	63.82	117.60	92.05	66.49	88.16
7	110.65	87.53	64.40	115.79	91.45	67.11	120.90	95.34	69.78	91.44
8	110.56	87.44	64.32	115.74	91.40	67.06	120.93	95.37	69.81	91.40
9	110.86	87.74	64.61	116.07	91.73	67.39	121.28	95.72	70.17	91.73
10	107.75	84.63	61.50	112.87	88.53	64.19	117.99	92.44	66.88	88.53
11	109.46	86.33	63.21	114.58	90.24	65.90	119.71	94.16	68.60	90.24
12	109.45	86.32	63.20	114.58	90.23	65.89	119.71	94.15	68.59	90.24
13	111.35	88.23	65.10	116.54	92.19	67.85	121.72	96.16	70.61	92.19
14	111.79	88.67	65.55	117.00	92.66	68.32	122.21	96.65	71.10	92.66
15	110.05	86.93	63.80	115.20	90.86	66.52	120.36	94.80	69.24	90.86
16	112.54	89.41	66.29	117.75	93.41	69.07	122.95	97.39	71.83	93.41
17	110.26	87.14	64.02	115.44	91.10	66.76	120.57	95.01	69.45	91.08
18	109.13	86.01	62.88	114.24	89.90	65.56	119.32	93.76	68.20	89.89
19	112.44	89.31	66.19	117.67	93.33	68.99	122.87	97.31	71.76	93.32
20	109.83	86.71	63.59	114.98	90.64	66.30	120.09	94.54	68.98	90.63
21	112.72	89.60	66.47	117.95	93.60	69.26	123.15	97.60	72.04	93.60
22	112.30	89.18	66.05	117.50	93.16	68.82	122.69	97.13	71.57	93.16
23	111.10	87.98	64.86	116.27	91.93	67.59	121.40	95.84	70.29	91.92
24	106.83	83.70	60.58	111.90	87.56	63.22	116.97	91.42	65.86	87.56
25	109.65	86.53	63.41	114.83	90.49	66.15	120.01	94.45	68.90	90.49
26	111.70	88.58	65.45	116.90	92.56	68.22	122.11	96.55	70.99	92.56
27	110.55	87.43	64.30	115.74	91.40	67.06	120.94	95.38	69.82	91.40
Mean	110.11	86.98	63.86	115.27	90.92	66.58	120.41	94.86	69.30	90.92

Note: Superscript n represents the experimental runs in external array.

Significance of Taguchi Method in Profit Optimization of CFU



- ☐ **Taguchi Method**

  243 experiments
  (= 27 x 9)

- ☐ **Full Factorial Design Method**

  19, 683 experiments
  (= 3^9)

Descriptions of Statistical Tools used in Taguchi Method

Response Plot

Determine the significance of individual factors based on the response plot's steepness

Visually determine the levels of individual factors yielding the maximum profit

Identify optimal configuration of factors

ANOM
ANOVA

Measure the significance of factors quantitatively

Ranking of importance of factors based on the highest percentage contribution, C_k^m

SNR

- Uphold "the-larger-the-better" quality principle for profit optimization purpose
- Determine the significance of factors towards the stabilization of disturbances

Statistical Tools: SNR, ANOM and ANOVA

- **Signal-to-Noise Ratio (SNR)**

$$(SNR)^n = -10log(MSD)^n$$

where N=27 is the no. of exp. in the internal array

$$(MSD)^n = \frac{1}{M}\sum_{m=1}^{M}\frac{1}{(x^{mn})^2}$$

where M=9 is the no. of exp. in the external array

Mean Squared Deviation (MSD) is defined to uphold the "**the larger the better**" quality principle.

- **Analysis of Means (ANOM) and Analysis of Variance (ANOVA)**
  - ☐ Average of factor K at level L in Case m, $\bar{x}_{kl}^{m}$

$$\bar{x}_{kl}^{m} = \frac{1}{N_R}\sum_{n=1}^{N_R} x_{kl}^{mn}$$

where N_r = 9, K = 9 and L = 3 are correspondingly the no. of repeated levels, controllable factors and levels

Statistical Tools: SNR, ANOM and ANOVA

- **Analysis of Means (ANOM) and Analysis of Variance (ANOVA)**
  - ☐ Average of factor K over all levels L in each Case m, $\bar{x}_k^m$

$$\bar{x}_k^m = \frac{1}{L}\sum_{l=1}^{L} \bar{x}_{kl}^m$$

  - ☐ Variance, V_k^m

$$V_k^m = \frac{\sum_{l=1}^{L}(\bar{x}_{kl}^m - \bar{x}_k^m)^2}{L_k^m - 1}$$

The denominator is called the
Degrees of Freedom, $(\boldsymbol{DOF})_k^m$
of factor k over all levels L in case m.

  - ☐ Percentage Contribution, C_k^m

$$C_k^m = \frac{100V_k^m}{\sum_{k=1}^{K} V_k^m}$$

Results: Averaged Profit Analysis

- Ranking of factors, R_k from ANOM (Descending Order: **A, C, H, I, G, D, F, B, E**)

	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
Level 1	92.48	90.93	89.88	91.05	90.93	90.80	91.22	90.44	91.33
Level 2	90.96	90.93	90.83	91.00	90.90	90.91	91.01	90.96	90.95
Level 3	89.32	90.91	92.05	90.72	90.94	91.06	90.54	91.36	90.49
$\bar{x}_k$	90.92	90.92	90.92	90.92	90.92	90.92	90.92	90.92	90.92
D_k	1560.30	10.28	1126.66	132.67	19.17	136.10	297.47	441.16	404.97
E_k	3158.35	26.05	2166.18	338.72	12.90	257.72	683.90	922.45	836.13
R_k	1	8	2	6	9	7	5	3	4

- Ranking of factors, R_k from ANOVA (Descending Order: **A, C, H, I, G, D, F, E, B**)

	Controllable Factors								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
$(DOF)_k$	2	2	2	2	2	2	2	2	2
V_k	2494854.10	192.37	1178777.95	32722.27	527.52	16762.11	122866.38	213934.54	175293.46
C_k	58.90	0.00	27.83	0.77	0.01	0.40	2.90	5.05	4.14
R_k	1	9	2	6	8	7	5	3	4

Results: SNR Analysis

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$(SNR)^n$	98.39	98.38	98.58	98.13	98.35	98.19	98.56	98.56	98.59	98.23	98.43	98.43	98.64	98.69
Run	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	
$(SNR)^n$	98.50	98.77	98.52	98.39	98.77	98.47	98.80	98.75	98.61	98.12	98.46	98.68	98.56	

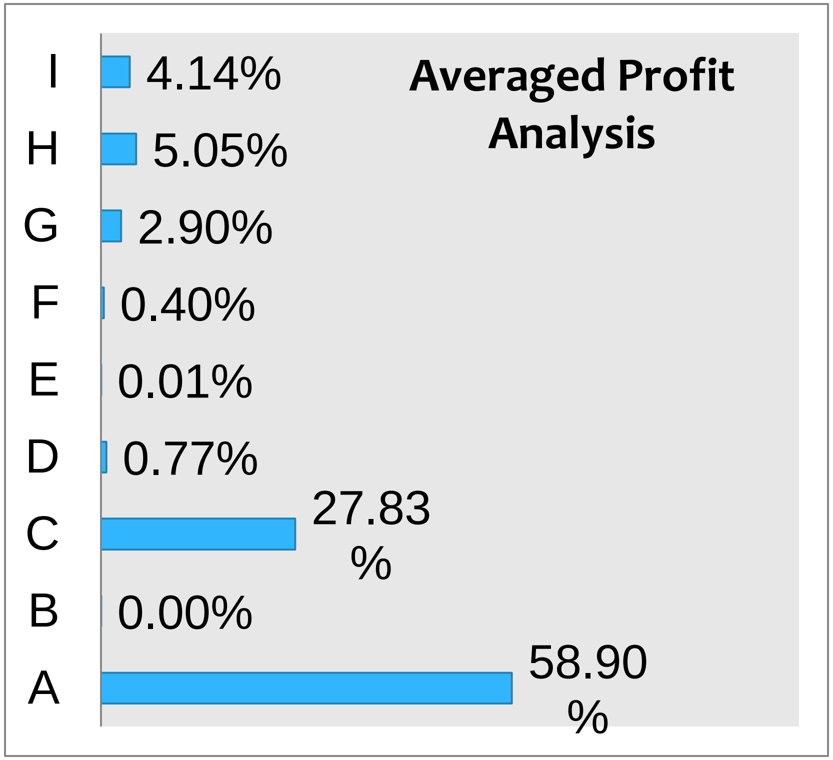
- Ranking of factors, R_k from ANOM (Descending Order: **A, C, H, I, G, D, F, E, B**)

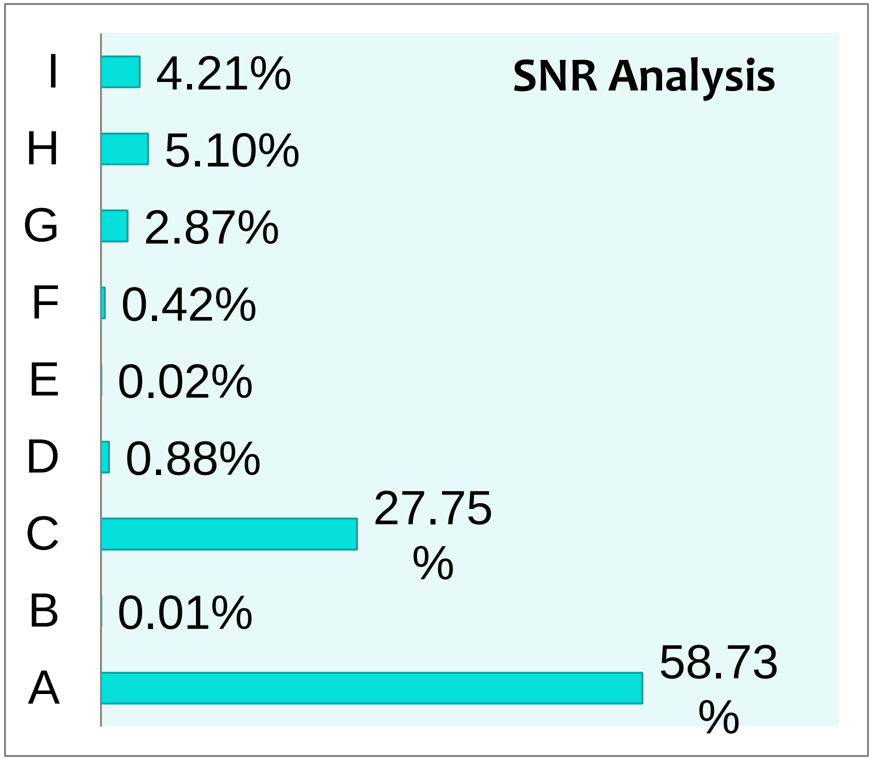
	Controllable Factors								
	$\overline{SNR}_{Al}$	$\overline{SNR}_{Bl}$	$\overline{SNR}_{Cl}$	$\overline{SNR}_{Dl}$	$\overline{SNR}_{El}$	$\overline{SNR}_{Fl}$	$\overline{SNR}_{Gl}$	$\overline{SNR}_{Hl}$	$\overline{SNR}_{Il}$
Level 1	98.67	98.51	98.39	98.52	98.50	98.49	98.53	98.45	98.55
Level 2	98.51	98.50	98.49	98.51	98.50	98.50	98.51	98.51	98.51
Level 3	98.32	98.50	98.63	98.48	98.50	98.52	98.46	98.55	98.45
$\bar{x}_k$	98.50	98.50	98.50	98.50	98.50	98.50	98.50	98.50	98.50
E_k	0.3507	0.0054	0.1341	0.0397	0.0061	0.0296	0.0755	0.1030	0.0938
R_k	1	9	2	6	8	7	5	3	4

- Ranking of factors, R_k from ANOVA (Descending Order: **A, C, H, I, G, D, F, E, B**)

	Controllable Factors								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
$(DOF)_k$	2	2	2	2	2	2	2	2	2
V_k	3.08E-02	7.56E-06	1.45E-02	4.60E-04	1.03E-05	2.20E-04	1.50E-03	2.67E-03	2.21E-03
C_k	58.73	0.01	27.75	0.88	0.02	0.42	2.87	5.10	4.21
R_k	**1**	**9**	**2**	**6**	**8**	**7**	**5**	**3**	**4**

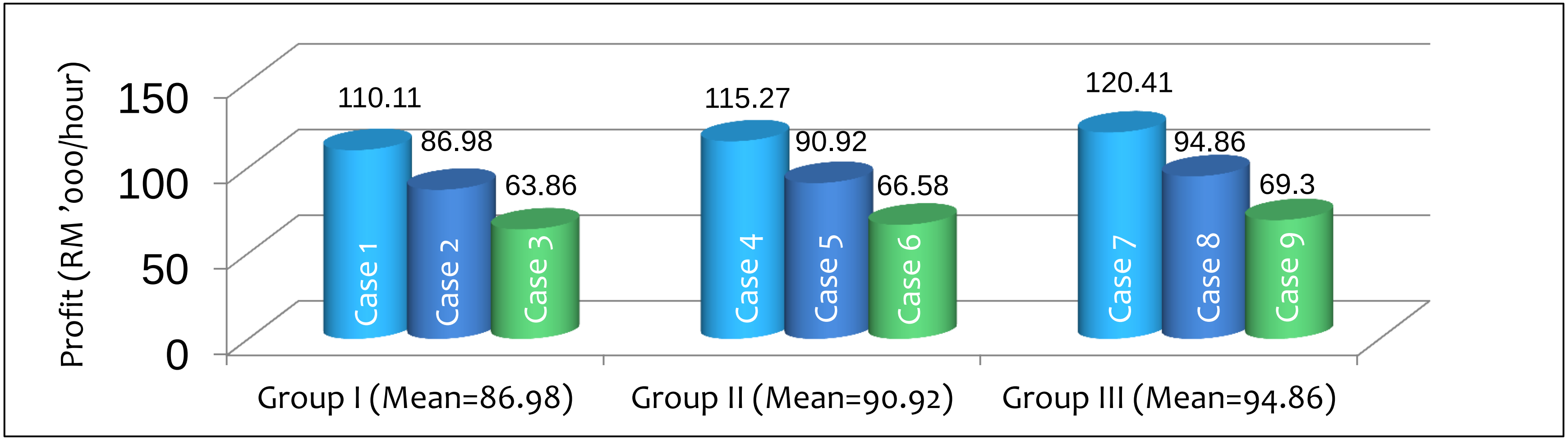
Analysis of Results: Percentage Contribution of Factors in Averaged Profit and SNR Analysis





- ☐ A factor with the highest C_k value is the most significant
- ☐ Results of Averaged Profit and SNR are found identical
- ☐ Ranking of factors, R_k in descending order of importance: A, C, H, I, G, D, F, E, B

Analysis of Results: Effects of Noise Factors



- ☐ A difference of about 4000 RM/hour is noticed between Groups I and II and between Groups II and III.
- ☐ This difference is caused by the presence of noise factor J (plant load).
- ☐ Increasing the plant load increases the amount of Condensate feed and thus CFU profit

- ☐ The highest values of average profit in each Groups I, II and III are generated from K_1 (factor K, level 1) configuration (Case 1, 4 and 7).
- ☐ Highly priced condensate feed decreases the CFU profit while the cheaper one increases it.

1. Optimal Configuration from SNR Analysis
2. Significance of Individual Factors

SNR

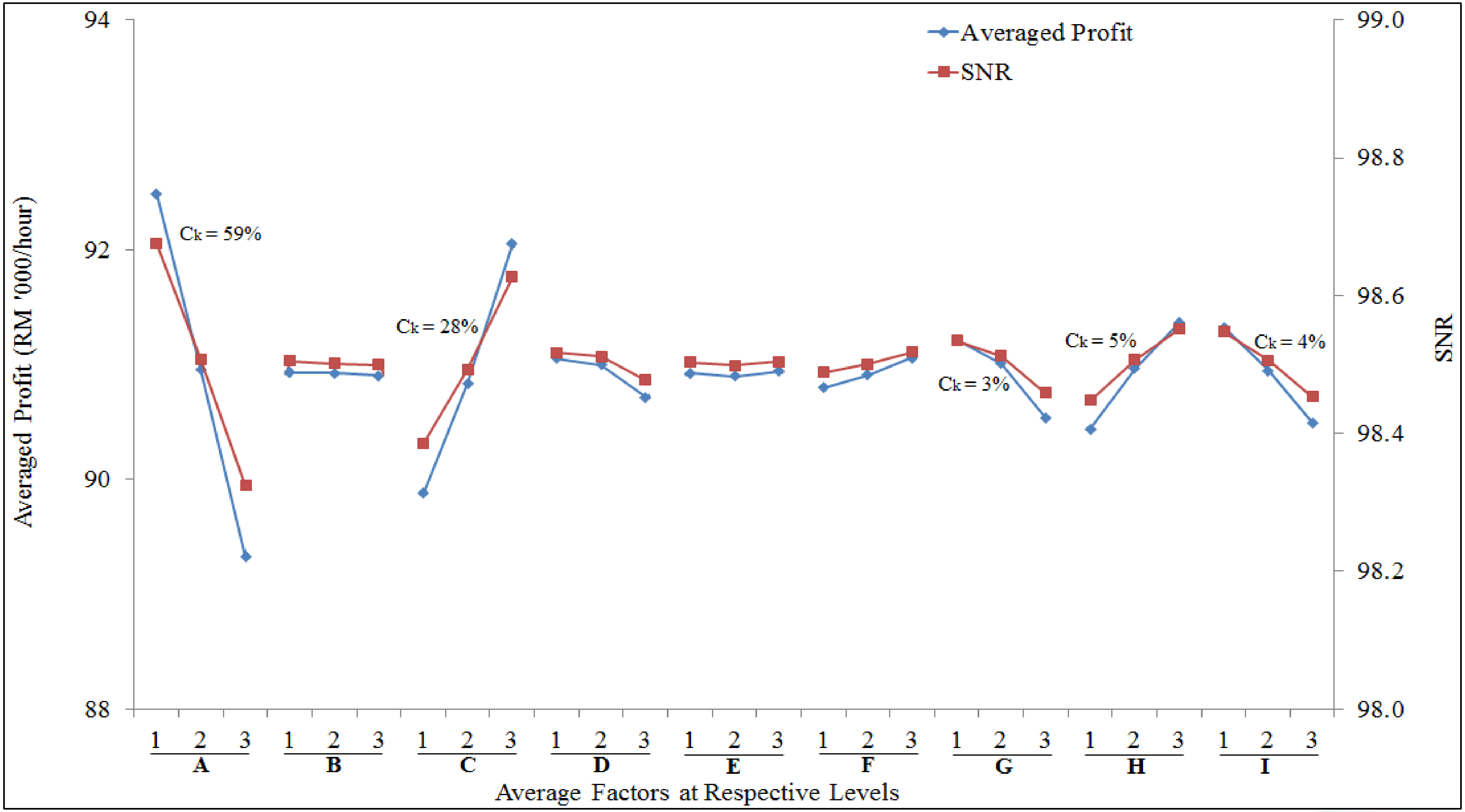
❑ The highest SNR value 98.80 comes from Run 21 with configuration A_1 B_3 C_3 D_3 E_1 F_1 G_1 H_3 I_3 yielding a maximum profit value of 123,154 RM/h at Case m=7 from all 243 experiments.

❑ The lowest SNR value 98.10 comes from Run 24 with configuration A_3 B_2 C_1 D_3 E_3 F_2 G_1 H_1 I_3 yielding a minimum profit value of 60,580 RM/h at Case m=3 from all 243 experiments.

Contributions

Factor A	❑ Controlling of C-101 top-stage temperature in which it affects the rate of production of wild naphtha, kerosene and diesel
Factor C	❑ Controlling of kerosene flow rate constraint. An increase in factor C increases the kerosene production which further contributing towards a higher profit (highest economic value)
Factors H I G	❑ The factors are employed to manipulate the operating temperature and pressure of C-104 which bring variation in term of LHN and HVN production flow rates

Response Plots of Averaged Profit and SNR Analysis



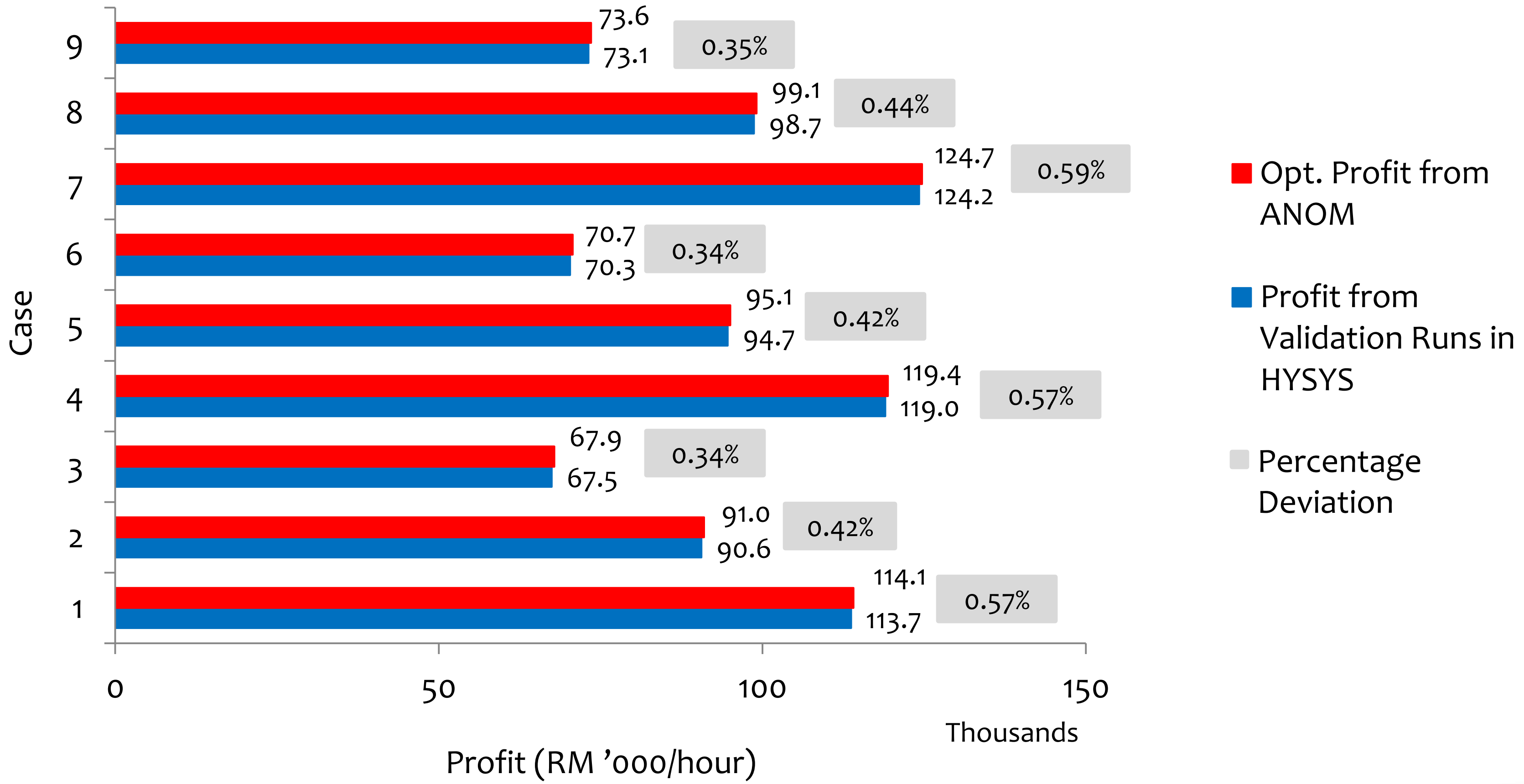
- ☐ Optimal configuration of controllable and noise factors are $A_1B_1C_3D_1E_3F_3G_1H_3I_1J_3K_1$, which yield the highest profit value of **124,247 RM/hour**.

Statistical Tools: SNR, ANOM and ANOVA

- **Optimum Profit**
  - ☐ Summation of global mean, $\bar{x}^m$ for the same case with maximum differences of average values of factor k at level l, $\bar{x}_{kl}^m$ from the corresponding average values at all levels, $\bar{x}_k^m$
  - ☐ Additional 9 runs of experiments are required

$$\boxed{x_{opt}^m = \bar{x}^m + \left(\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m\right)}$$

Comparison between Experimental Results from Validation Runs and Calculated Optimum Profit from ANOM



- ☐ Small deviation values of less than 1% for all Cases 1-9 are obtained.

Profit Optimization of CFU using Taguchi Method

CONCLUSION

Significance of 9 controllable and 2 noise factors influencing the CFU profit is studied by conducting 243 experiments in a Taguchi crossed-orthogonal array set up.

A total percentage contribution of 98.2% from 5 controllable factors (A, C, G, H and I) while the others 4 factors are found trivial.

Maximum CFU profit acquired from an optimum configuration based on the response plots of the averaged profit and SNR analysis.

Average deviation of 0.45% in all cases (9 validation runs) between the experimental results and calculated optimum profit from ANOM equation.

Improved profit further verifies the optimality of configuration.

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