Taguchi's Parametric Design Approach for Determining the Significant Decision Variables in a Condensate Fractionation Unit (CFU)

By

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(LEE CHIA CHUN)

ABSTRACT

Taguchi's parametric design approach is employed to systematically determine the significant decision variables and their respective optimal levels contributing towards the most profitable operation of a Condensate Fractionation Unit (CFU). The present work aims to reduce the frequent optimization issues such as high market dynamics in term of fluctuation of price of condensate feedstock and products as well as the difficulties in determining the decisive variables for effective implementation of optimization strategy. For this purpose, a steady-state CFU model developed under HYSYS environment is used as a virtual plant to carry out the fractionation processes. Experiments are designed and executed by utilizing the combination of process parameters (9 controllable and 2 noise factors) based on three-level of L_{27} and L_9 orthogonal arrays. The results are interpreted using analytical tools such as analysis of mean (ANOM), analysis of variance (ANOVA), signal-to-noise ratio (SNR) analysis and response plot. Five controllable factors handling the pressure, temperature and product flow rates top the ranked list with a total contribution of 98.2%. The maximum profit is obtained from an optimal configuration of both controllable and noise factors. Remarkable agreements with an average deviation of 0.45% are found in all cases when the implemented results are validated against those suggested by ANOM and the improved profit further verifies the optimality of configuration. The outcome from this work imply that Taguchi method can be employed in other processes due to its robustness in handling noise factors with the minimum number of experiments.

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CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 Background of Study

1.1.1 An Overview of the Refinery Industry

Refineries are a complex network of processes which convert crude oils into a range of refined products (most notably liquefied petroleum gases (LPG), gasoline, jet fuel, kerosene, diesel fuel, petrochemical feedstock, lubricating oils and waxes, fuel oil and asphalt) through a sequence of physical and chemical transformations. In another word, refineries are processes that convert crude oil curve to the product demand curve (Young, R. E., 2006). They convert the low value molecules into higher value molecules, and blend hydrocarbon fractions into various streams of products.

Each refinery would have a unique physical configuration, as well as their unique operating characteristics and economics. It is noteworthy that certain refineries are configured to maximize gasoline production or to maximize the distillate (diesel and jet fuel) production while in some regions, petrochemical feedstock production has become their main concerns due the fast demand growth on those products. A typical feedstock for a petroleum refinery will be the crude oil which range from the smallest hydrocarbon molecule (CH_4) to large and complex molecules containing up to 50 or more carbon atoms.

In the current study, instead of crude oil, a condensate feedstock will be used in a condensate fractionation unit (CFU) to produce refined products such as fuel gas, Liquefied Petroleum Gas (LPG), light naphtha (LHN), heavy naphtha (HVN), kerosene and diesel. Condensate feedstock is taken from offsite storage tank, and blended in the required ratios before entering the unit. From series of separation processes, products as discussed before will be sent to other units for further processes or storage before hitting the market. Condensate is composed of various hydrocarbons with the wide range of BP. The condensate feedstock could be divided into the following products from the view point of BP.

Table 1-1: Normal BP of hydrocarbons and carbon symbols.

Hydrocarbon	**Normal BP (℃)**	**Carbon Symbol**
Uncondensed gas (methane, ethane)	< 30	C1-C2
LPG (butane, propane)	< 30	C3-C4
LHN	~ 30	C5-C6
HVN	30-200	C7-C11
Kerosene	200-300	C12-C17
Diesel	> 300	C13-C17

The hydrocarbons of condensate feedstock are similar to the crude oil except naphtha fraction in the condensate feedstock is much larger than that of the ordinary crude oil. The heaviest component fraction in the condensate feedstock also is much lesser than that in the ordinary crude oil. Hence, there is no heaviest product such as bitumen produced from the condensate feedstock.

1.1.2 Challenges of Refinery Industry

All the refining profits heavily rely on producing finished products that yield the highest margins from the lowest crude oil while in the meantime maintain the optimum plant operating efficiency. However, due to the fast growing competition and emergence of new technologies, product demand (from local and/or export markets), stringent product quality requirements and environmental regulations and standards especially among the gas and petroleum refinery industries, the plants are increasingly compelled to operate profitably in a more dynamic way.

Such challenges can be handled through real time optimization (RTO) and advanced process control (APC) where these optimization strategies can be suitably fit in to determine the most cost-effective and efficient solution to a problem or design for a process as well as the major quantitative tools in industrial decision making. The ultimate goal of optimization is to determine the values of the variables in the process that yield the best value of the performance criterion. In another words, it is to select the best among the entire set of solutions by efficient quantitative methods. In plant operations, benefits come from the improved plant performance such as improved product yields, reduced energy utilization, higher processing rates, reduced maintenance costs and etc. Hence, a systematic method in determining the significant decision variables is needed for the effective implementation of optimization strategy and this can be achieved through Taguchi method.

1.1.3 Taguchi Method

Taguchi method is a powerful statistical technique to produce high quality product and optimize the process design problems in a cost efficient way by reducing process variation through robust design of experiments. Consistency of process performance can be achieved by making a system insensitive towards the influences of various uncontrollable factors (Ranjit Roy, 2001).

Its contributions to the discipline and structure of DOE offer an alternative solution where the conventional factorial design is simplified into a unique methodology involved the establishment of a series of experiments through the balanced characteristic of orthogonal array, a unique icon of Taguchi method, to identify the optimal combination of the parameters which has the most influence on the performance and least variance from the targeted design standard (Yang, K. et al., 2007). Taguchi method is used an off-line optimization technique where it involves a three-stage process, namely, system design, parametric design and tolerance design. The system design deals with the working levels of design factors where the development and testing of a system are performed based on the scientific and engineering knowledge. At the stage of parametric design, an optimum condition is determined at specific factor levels with or without the presence of uncontrollable factors. The third stage is the tolerance design, which is used to fine tune the optimum factor levels obtained from the parametric design stage (Yusoff et al., 2011). This step is vital in tightening the product quality, reducing the capital and operating costs as well as meeting the customer satisfaction index. In the present work, parametric design is employed to determine the optimal level of process parameters leading to the plant profit optimization.

1.2 Problem Statement

1.2.1 Fluctuation of Market Price of Condensate Feedstock and Products

The optimization of the petroleum refinery industry remained challenging due to the frequent fluctuation of feedstock price and the values of its products depending on the market conditions. The inconsistency issue happened as the market dynamics are taken into account in real time to calculate the most profitable operating mode for the plant to achieve its highest profit.

1.2.2 Challenges in Determining the Significant Decision Variables for Effective Implementation of Optimization Strategy

In steady-state optimization, a plant model usually contains several hundreds of variables available for manipulation. For instance, a dynamic model of a refrigerated gas plant under Aspen HYSYS environment contains 762 variables and 21 regulatory loops (Yusoff et al., 2008). In this context, the Taguchi's parametric design approach will be used in the selection of the control and optimization variables which are significant towards the process optimization.

1.3 Objective

The objective of the present work is to systematically determine the significant decision variables for profit optimization of CFU using Taguchi method as the design of experiment (DOE). Means to achieve the objective are as below:

- Identify and rate controllable factors under influence of noise factors.
- Determine the optimal configuration of controllable and noise factors.
- Estimate and validate the maximum profit within the constraints of all factors.

1.4 Scope of Study

1.4.1 An Overview of Condensate Fractionation Unit (CFU) Process

In the present work, a steady-state CFU model is developed in HYSYS environment and used as a test bed to conduct the experiment. CFU is designed to fractionate condensate into valuable products such as LPG, LHN, HVN, kerosene and diesel. It is made up of a series of fractionator and distillation columns, namely the Condensate Fractionator Column (C-101), Kerosene Stripper Column (C-102), Naphtha Stabilizer Column (C-103) and Naphtha Splitter Column (C-104). Condensate from storage will be heated up in a series of heat exchangers before entering the C-101. In C-101, wild naphtha will be stripped off overhead and kerosene will be separated as side draw to C-102. Bottom product which is diesel will be routed to storage while the overhead wild naphtha will be routed to the C-103 where the LPG will be separated overhead and Petrochemical Naphtha (PCN) which consists of LHN and HVN at the bottom. The LPG will be sent to LPG sphere for storage. PCN from the bottom of C-103 will be separated to LHN and HVN stream in the C-104. Here, LHN will be removed overhead while HVN will be removed at the bottom. Process flow diagram (PFD) and detailed process description of CFU will be discussed in **section 3.3**.

1.4.2 Process Variables and Case Studies

The terms namely, variables, parameters and factors are synonyms used throughout this paper. Factors can be categorized into controllable and noise factor. The former is used to manipulate the process while the latter is used to evaluate the degree of severity of their effects to the desired process. There are 9 controllable factors (*A* to *I*) and 2 noise factors (*J* and *K*) selected in the current work.

Case studies are generated based on the Taguchi DOE of noise factors *J* and *K* in different levels (low, medium and high). A cross-orthogonal array layout consists of internal (controllable factors) and outer arrays (noise factors) are further applied in the DOE to study the effects of numerous process factors towards the profit optimization of CFU. Detailed descriptions and levels of variables will be further elaborated in **section 3.3**.

Table 1-2: General Description of Process Variables

Factor	**Unit**	**Description**
A	℃	C-101 Stage 28 Temperature
B	℃	C-101 Bottom Stage Temperature
C	kg/hr	C-102 Kerosene Prod. Flow Rate
D	kg/hr	C-101 Top Pump-Around Flow Rate
E	℃	C-103 Top Stage Temperature
F	kPa	C-103 Top Stage Pressure
G	℃	C-104 Bottom Stage Temperature
H	℃	C-104 Top Stage Temperature
I	kPa	C-104 Top Stage Pressure
J	kg/hr	Condensate Flow Rate (Plant Load)
K	RM/kg	Condensate Price

CHAPTER 2

LITERATURE REVIEW

2 LITERATURE REVIEW

2.1 Optimization of Industrial Processes

In recent years, oil and gas refiners have run into difficult challenges which require the refinery operators to have a heightened awareness towards the aspects of safety, emissions as well cost reduction issues (Schowalter, D., 2008). Refiners must be able to improve unit operation reliability, reducing operation losses while in the meantime conserving energy. Hence, refinery industries in the world are increasingly opting for various optimization strategies in order to increase unit operation efficiency and reliability which making their operation more profitable and safer.

Optimization of a large configuration of plant components can involve several levels of detail ranging from the most-minute features of equipment design to the grand scale of international company operations. An important global function of optimization is the synthesis of the optimal plant configuration. By synthesis it means the designation of the plant elements, such as the unit operations and equipment. A major use of optimization is in the detailed design or retrofit of a plant for which the flow sheet is already formulated. Goals are to enhance profitability; reduce utility costs; select raw materials; size equipment; and analyses reliability, flexibility, and safety and etc.

An even more widespread application of optimization is the determination of the optimal operating conditions for an existing plant such as the selection of temperatures, pressures, flow rates and etc. (Edgar, T. F., 2001). Figure 2.1 illustrates the flow chart of determination of the optimal plant operating conditions. Optimization is playing an important role at both the intermediate stages of the process simulator and overall economic evaluation.

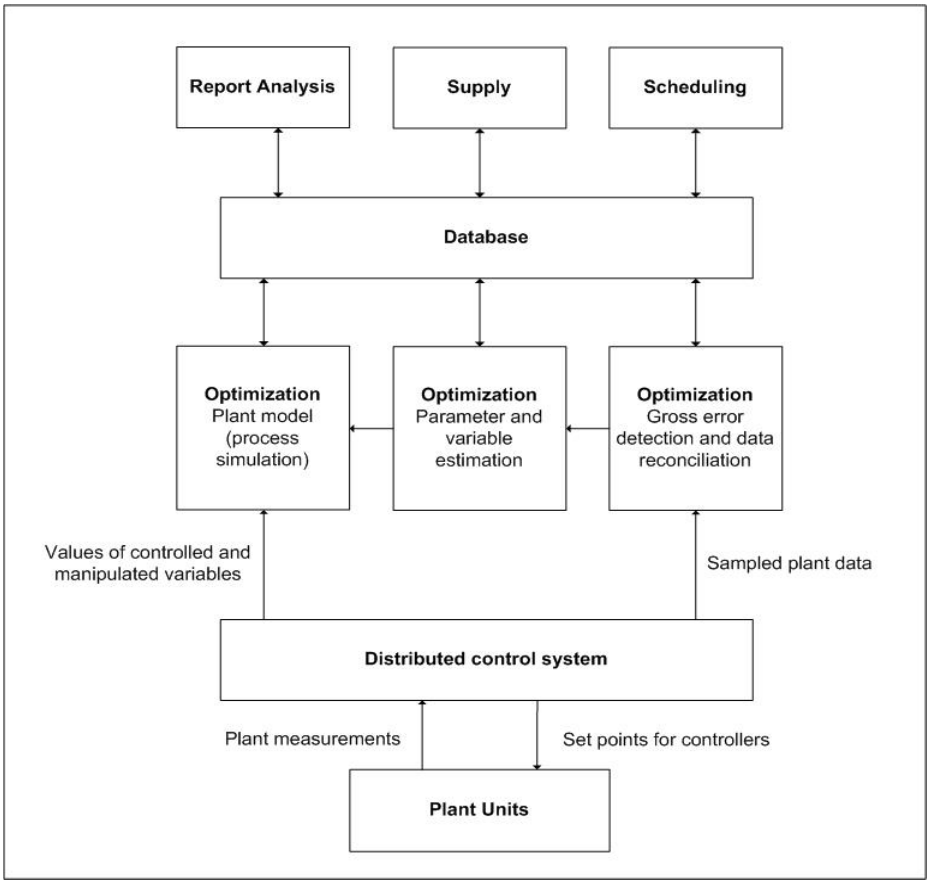

Figure 2-1: Flow chart of determination of optimal plant operating conditions.

Shokri, S. et al. (2009) demonstrated numerous successful applications of optimization technology in oil refinery industry where an increased profit was achieved with higher plant's performance by maintaining the operation in optimum condition. In an extensive study by Asadi, I. et al. (2011) regarding the investigation on effect of real time optimization in the gas sweetening plant in Iran, a 30-40% reduction of energy consumption respect to various disturbances have been achieved successfully. In his paper, the entire plant simulation was modeled through HYSYS with Kent-Eisenberg equation of state as the thermodynamic properties. A nonlinear, steady-state and inequality constraints equipped model was generated to study the objective function in improving the overall economic performance of the plant. The author was able to achieve a profit increment of 20MM$/year under various disturbances due to new optimum set points.

Application of optimization can also be seen in Malaysia where Shell Malaysia E&P implements the technology in its integrated Gas Production System in Sarawak for the purposes of real-time monitoring and optimization of facilities and wells. In an extensive study conducted by Gobel, D. et al. (2011), the authors describe the optimization approaches applied by Shell in maximizing condensate revenue through an automated data-driven system covers more than 1000 variables spanning a gas production network of more than 100 wells and 40 platforms. The results showed a consistent gas supply and improved timely operational decisions as well as a physically realistic, stable; adhere to contractual and commercial constraints and most importantly a relative short payback time.

2.2 Taguchi's Parametric Design Approach

As mentioned earlier in the problem statement, a plant model usually contains several hundreds of variables available for manipulation. Hence, for an effective implementation of optimization strategy, a proper selection of optimization variables which are significant towards the process optimization is required.

Factorial and fractional factorial designs are widely used and recognized techniques especially in the process of investigating all possible conditions in an experiment which involved multiple factors. Factorial design overcomes the drawbacks of one-at-time changes through increasing number of experimental runs in terms of producing higher accuracy parameters (Spall, J. C., 2010). However, these approaches possess certain limitations where they required strict and complicated mathematical treatment in the design of experiment as well as to analyse the results. It would be costly and time consuming to perform all the experiments and completely different results may be obtained from two designs of the same experiment.

Herein lays Taguchi's contribution to the science of the design of experiments. Taguchi contributed discipline and structure to the design of experiments. The result is a standardized design methodology that can easily be applied by investigators. Furthermore, designs for the same experiment by two investigators will yield similar data and will lead to similar conclusions (Roy, R. K., 2010). Taguchi method offers an alternative solution where the conventional factorial design is being simplified into a unique methodology involved the establishment of a series of experiments to identify the optimal combination of the parameters which has the most influence on the performance and least variance from the targeted design standard (Yang, K. et al., 2007). The balanced characteristics of cross-orthogonal arrays layout consists of inner and outer arrays are used in industrial experiments to study the effects of numerous process factors (Hartaj Singh, 2012). The inner array made up of the orthogonal array of possible combinations of controllable factors while the outer array comprises of the combinations of uncontrollable factors.

In an extensive study conducted by Antony, J. (2006), "Taguchi or classical design of experiments: a perspective from a practitioner", the author explained the important elements and critical dissimilarities between the classical DOE and the Taguchi method. As for the fundamental differences, Taguchi method uses a large experiment to study all the main effects and the important interactions. Various process parameters and their interactions are being assigned in special designed orthogonal array where it has the ability to significantly reduce the number of experiments required to determine the optimal conditions. On the other hand, classical DOE promotes the sequential and adaptive approach to experimentation. SNR is being applied in Taguchi method to study the mean response and response variability which contribute to toward the process robustness. The effect of hard-controlled noise parameters which caused inconsistency in process performance can be minimized through the marginal average plot of SNR. In classical DOE, experimenters are not interested to study the effect of noise parameters.

Since both the classical DOE and Taguchi method apply different terminologies and techniques, it is important for the experimenter to select appropriate strategy based on the nature of the problem. The Taguchi method can be used when the problem required rapid understanding of the process and fast respond to the management; when noise parameters are identified as a source of process variation; to achieve process robustness and to set tolerances on the design parameters. Conversely, classical DOE should be implemented when the experimenter is anticipated to predict a target value for the performance characteristic of process; to develop a mathematical model connecting the process response and when the experiments with strong interactions are required. Apart from the nature of problem, selection of appropriate strategy for process optimization and parametric design is largely depends on the degree of optimization required, level of difficulty in term of implementation, time and cost factors, amount of training, statistical validity and robustness of approach.

Nevertheless, SNR remains one of the most controversial contributions of Taguchi as some western statisticians argued that sample mean and variance should be analysed separately since both of them are stochastically independent for a Gaussian process (Maghsoodloo, S. et al., 2004). In some cases for parameter design where the mean and variance are analysed separately and the results presented show slight disagreement with the results obtained from the use of SNR. Nonetheless, there are also cases where both the SNR and analysis of mean and variance show good agreements in term of optimum configuration as well as significance of parameters.

Recently, Taguchi method has been successfully implemented in assorted areas of applications such as engineering, biotechnology, automobile, aerospace and other industries. Two similar studies in determining the optimum conditions to remove dyes using Taguchi method were found. Engin, A. B. et al. (2008) used a L_{16} orthogonal array while Barman, G. et al. (2011) selected a L_{25} design in their respective studies on effects of process parameters such as concentration, contact time, temperature and pH level towards the optimum dyes removal conditions. Both the authors defined the optimum condition with the performance statistic of “the larger the better” and SNR as well as ANOVA were used for the analysis of results. It is noteworthy that the both the results show certain degree of agreement in which the concentration factor has the biggest contribution towards the dyes removal process. Taguchi approach has contributed in parameter selection in both the above optimization cases of dyes removal process and furthermore, the studies helped to conserve the environment as an efficient way to remove coloring materials from effluents was discovered.

Cheng et al. (2008) studied thermal chemical vapor decomposition of silicon film by integrating computational fluid dynamic codes in FLUENT and a dynamic model of Taguchi method with L_{18} orthogonal array. Thickness deviation of silicon film was found to be reduced by up to 11% points from 36% previously. In another application, Chiang (2005) studied cooling performance of a parallel-plain fin heat sink module using L_{18} (2^1 x 3^7) arrays. Through the analysis of variance (ANOVA), four out of eight variables, namely number of opening slots (34.8%), surface area of copper base (23%), fan capacity (14%) and height of fin flake (9%), were found to give a significant contribution to the cooling process. By using the optimal configuration of these variables in a simulated environment, the author achieved a 15% improvement in the cooling process. Lee and Kim (2000) used a parallel-mechanism machine tool containing eight servo drivers as the test bed in their study of controller gain tuning technique for multi-axis PID control system. By utilizing an L_9 (3^4) orthogonal array, robust controller gains were obtained. A performance indicator namely the index of average position and velocity errors was successfully reduced by 61.4%. Apart from that, the authors achieved a 8.5 dB increment in the average signal-to-noise ratio to reach better control of the machine tool.

Yusoff, N. et al. (2011) studied the Taguchi's parametric design approach for the selection of optimization variables in a refrigerated gas plant (RGP) with the objective to determine the maximum RGP profit within the specific constraints of all variables. The author used a dynamic model of RGP under HYSYS environment as test bed to perform the simulation. Seven controllable factors namely split range controller SRC103 output, temperature controller TC101 output, split range controller SRC102 output, ratio controller RC101 ratio, flow controller FC104 output, demethanizer C-101 overhead pressure and temperature controller TC102 output and 2 uncontrollable factors namely feed gas flow rate and feed gas prices were being studied in L_{27} and L_9

orthogonal arrays respectively. Statistical tools like SNR, ANOM and ANOVA were used to analyse the results. Three controllable factors were found to be the most influential parameters toward the reduction of energy utilization, namely the SRC103 output and TC101 output where higher values of these factors enhanced the controlling of entire plant temperature while the TC102 output helps to ensure a smooth separation of feed gas in the demethanizer. On the other hand, for the uncontrollable factors, the feed gas flow rate was found to be the more significant variable compared to the feed gas prices as a higher plant load can contribute to a higher production of sales gas and natural gas liquids products.

Ali, S. F. et al. (2012) applied Taguchi's parametric design approach in his study of determination of optimal cut point temperature at crude distillation unit (CDU). The author used the Taguchi method to select the optimal cut point temperatures for maximizing the diesel yield at the lowest possible energy utilization. A steady-state model of CDU was created in Aspen HYSYS environment to perform the fractionation process and a L_{18} orthogonal array was selected to study a total of 8 factors (cut-point temperature of off-gas, light S.R, naphtha, kerosene, light and heavy diesel, atmospheric gas oil and residue) and 3 levels respectively. The performance characteristic of "the lower the better" was selected. The result was analysed by using the statistical tools such as ANOM, ANOVA as well as the averaged energy/product response plots. It is noteworthy that the cut-point temperatures of kerosene and heavy diesel are the most significant factors contributing towards the optimization of diesel in CDU. The shifting of levels caused the diesel range to increase much wider compared to the base cases. Taguchi method has successfully increased the diesel production whilst decreased the energy utilization. The identified optimal configurations for all cases showed that 20-41% of optimization can be achieved as compared to the current straight run temperatures.

CHAPTER 3

RESEARCH METHODOLOGY

3 RESEARCH METHODOLOGY

3.1 Overview of Taguchi's Design of Experiment (DOE)

The methodology devised for the optimization of the economic performance in the current work is based on the Taguchi method and its implementation can be illustrated with the help of a flow diagram as shown in **Figure 3.1**. Step 1 is the problem formulation where the objective function is defined. In the case of CFU, the objective function is formulated into an economic expression which is to achieve the highest profit through the identification of the most profitable operating mode. Step 2 is to determine the process parameters (controllable and noise factors) that affect the process performance as well as their levels (low, normal and high). To obtain maximum plant profit, the-higher-the-better quality characteristic is selected. Step 3 is to select the orthogonal array based on the number of parameters and their respective levels of variation. Step 4 is to conduct the experiments based on the cross-orthogonal arrays set-up. A steady-state model of CFU under HYSYS environment is developed and used to run the experiment. Step 5 is to conduct the data analysis using statistical tools such as SNR, ANOM, ANOVA and response plot to determine the effect of the process parameters on the objective function. The final step deals with the validation of experiment where the significance of profit optimization is verified by conducting additional experiments using the identified optimal configuration. Detailed research methodology will be elaborated in **section 3.3**.

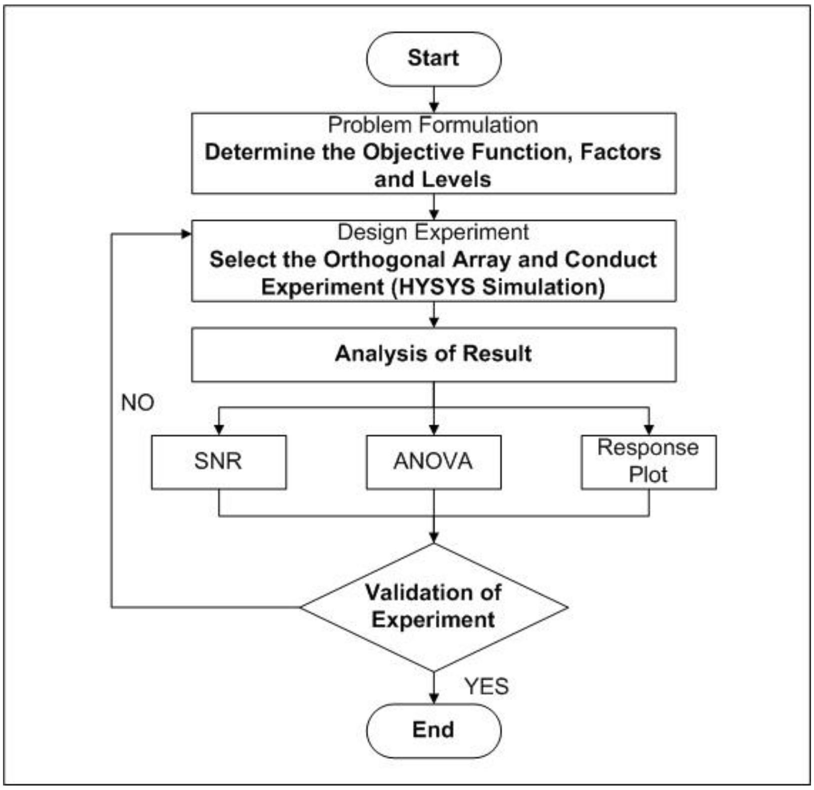

Figure 3-1: Flow diagram of Taguchi Method.

3.2 Software

3.2.1 ASPEN HYSYS

ASPEN HYSYS is a powerful process modeling tool which enables engineers to rapidly evaluate the safest and most profitable designs through creation of interactive models for “what-if” studies and sensitivity analysis. These models can be leveraged throughout the plant lifecycle from conceptual design to detailed design, rating and optimization. It significantly reduces costs and enabling better operating decisions.

3.2.2 Design-Expert Software

Design-Expert software designed to help with the design and interpretation of multi-factor experiments. The software offers a wide range of designs such as factorials, fractional factorials, Taguchi design and etc. It can handle both process variables as well as mixture variables and provide in-depth analysis of experiment. The software helps experimenter to identify the optimum spot which is the most desirable factor settings for multiple responses via its numerical optimization function.

3.3 Taguchi Method

3.3.1 Problem Formulation

The objective function is to achieve the highest profit through the identification of the most profitable operating mode based on the optimal configuration of both controllable and noise factors. The objective function (Eq. (1)) is formulated as the following economic expression.

$$P = \left\{ \sum_{i=1}^{I} R_i - C_{Feed} - C_{Utilities} \right\} \qquad (1)$$

where P is the profit, $R_i (I = 5)$ are the revenues, C_{Feed} is the cost of condensate feed and $C_{Utilities}$ is the operational expenses. Product values are the sales of refined products such as LPG, LHN, HVN, kerosene and diesel. Revenues will be calculated based on the flow rates of the respective products. The operational expenses are mainly due to the cost of utilities. The economics data which comprises of prices and corresponding units of component of revenues and expenses is shown in **Table 3.1**.

Table 3-1: Economics Data

Component	**Price**	**Component**	**Price**
Condensate	RM 2.49/kg	Kerosene	RM 3.37/kg
LPG	RM 2.54/kg	Diesel	RM 2.96/kg
LHN	RM 2.83/kg	Steam Duty	RM 89.90/MWh
HVN	RM 2.74/kg	Electricity	RM 233.30/MWh

NOTE: Economics data are based on inputs from optimization engineer in PP(T)SB.

3.3.2 Factors and Levels

In this paper, factors can be divided into controllable and noise factors and is specified and maintained at specific levels throughout the Taguchi experimental stage. Controllable factors are employed to manipulate the fractionation process whereas the noise factors are used to measure the degree of severity of their influences towards the particular process. For the selection of controllable and noise factors as well as the levels, inputs from experienced operators are essential. Description of factors and levels for CFU is shown in **Table 3.2**.

Table 3-2: Description of factors and levels

Factors	**Level 1**	**Level 2**	**Level 3**	**Units**	**Description**
A	122	124	126	℃	C-101 Stage 28 Temperature
B	304	306	308	℃	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-103 Top Stage Temperature
F	1137	1177	1217	kPa	C-103 Top Stage Pressure
G	150.4	151.4	152.4	℃	C-104 Bottom Stage Temperature
H	80.07	81.07	82.07	℃	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 (Plant Load)
K	2.42	2.49	2.56	RM/kg	Condensate Price

3.3.3 Taguchi Orthogonal Array

An L_{27} (3^9) orthogonal design made up of 9 controllable factors and 3-levels is used as the internal array whereas an L_9 (3^2) design made up of 2 noise factors and 3-levels is used as the external array throughout the experiment. In the current work, the L_{27} array consists of 27 rows and 9 columns (only 9 out of 13 columns are used) where rows and columns represent the experimental runs and controllable factors, respectively. On the other hand, the L_9 external array consists of 9 rows and 2 columns (only 2 out of 4 columns are used).

It is noteworthy that in order to measure the responses of all 9 controllable factors towards the objective function, only 27 experiments/runs from the internal array required to be conducted for each runs from the external array. Thus, a total of 243 (=27 x 9) experiments are required to be executed as compared to the conventional full factorial design approach which requires 19, 683 (3^9) experiments and this shows that Taguchi method is a more appealing strategy in this context. The reduced external and internal arrays and crossed-orthogonal arrays set up are shown in **Table 3.3, 3.4** and **3.5** respectively.

Table 3-3: Taguchi L_9 (3^2) External Array showing Levels of Noise Factors.

Factor	**Run**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
J	1	1	1	2	2	2	3	3	3
K	1	2	3	1	2	3	1	2	3

Table 3-4: Taguchi L_{27} (3^9) Internal Array showing Levels of Controllable Factors.

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

Table 3-5: Taguchi Crossed-Orthogonal Arrays Set-Up.

									Noise Factors	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
									J	330338	330338	330338	347724	347724	347724	365110	365110	365110
									K	2.42	2.49	2.56	2.42	2.49	2.56	2.42	2.49	2.56
Runs	**Controllable Factors**									**Profits (RM/hour)**								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**									
1	124	308	23139	321000	84	1217	150.4	80.07	106.4									
2	124	304	25710	353100	83	1177	152.4	80.07	106.4									
3	122	304	23139	288900	84	1177	151.4	81.07	106.4									
4	126	308	25710	288900	84	1137	152.4	80.07	109.4									
5	124	308	23139	321000	85	1137	151.4	81.07	109.4									
6	126	306	23139	353100	84	1137	152.4	82.07	106.4									
7	124	306	28281	288900	83	1177	152.4	81.07	109.4									
8	124	304	25710	353100	85	1137	151.4	82.07	103.4									
9	122	304	23139	288900	83	1137	150.4	80.07	103.4									
10	126	306	23139	353100	83	1217	151.4	81.07	103.4									
11	126	308	25710	288900	83	1217	151.4	82.07	106.4									

12	126	308	25710	288900	85	1177	150.4	81.07	103.4									
13	122	306	25710	321000	85	1217	152.4	80.07	103.4									
14	122	306	25710	321000	83	1137	150.4	81.07	106.4									
15	124	304	25710	353100	84	1217	150.4	81.07	109.4									
16	122	308	28281	353100	84	1177	151.4	80.07	103.4									
17	126	304	28281	321000	85	1177	150.4	82.07	106.4									
18	126	304	28281	321000	83	1217	151.4	80.07	109.4									
19	124	306	28281	288900	84	1217	150.4	82.07	103.4									
20	126	304	28281	321000	84	1137	152.4	81.07	103.4									
21	122	308	28281	353100	83	1137	150.4	82.07	109.4									
22	122	308	28281	353100	85	1217	152.4	81.07	106.4									
23	124	306	28281	288900	85	1137	151.4	80.07	106.4									
24	126	306	23139	353100	85	1177	150.4	80.07	109.4									
25	124	308	23139	321000	83	1177	152.4	82.07	103.4									
26	122	306	25710	321000	84	1177	151.4	82.07	109.4									
27	122	304	23139	288900	85	1217	152.4	82.07	109.4									

3.3.4 HYSYS Modeling of CFU

A steady-state model of CFU is developed under HYSYS environment to be used as a test bed to conduct the study. CFU in PETRONAS Penapisan (Terengganu) Sdn. Bhd. (PPTSB) is taken as reference in developing the model. The process flow diagram (PFD) of CFU is shown in **Figure 3.2**.

3.3.4.1 Design Specification of CFU

Table 3-6: Design Specification of CFU.

Equipment ID	Equipment Name	Operating Parameter	Value
C-101	Condensate Fractionator	Top Pressure (kg/cm^2g)	1.3
		Top Temperature (°C)	121
		Bottom Pressure (kg/cm^2g)	1.8
		Bottom Temperature (°C)	314
C-102	Kerosene Stripper	Top Pressure (kg/cm^2g)	1.4
		Top Temperature (°C)	159
		Bottom Pressure (kg/cm^2g)	1.9
		Bottom Temperature (°C)	252
C-103	Naphtha Stabilizer	Top Pressure (kg/cm^2g)	12.2
		Top Temperature (°C)	76
		Bottom Pressure (kg/cm^2g)	12.9
		Bottom Temperature (°C)	171
C-104	Naphtha Splitter	Top Pressure (kg/cm^2g)	1.2
		Top Temperature (°C)	76
		Bottom Pressure (kg/cm^2g)	1.9
		Bottom Temperature (°C)	152

3.3.4.2 Process Description of CFU

Condensate feedstock (22℃, 10.3 bar, 58 API) is introduced under flow control to CFU from storage. First, the condensate feed is heated by Condensate/Kerosene Exchanger E-100 (22 to 33℃) and Condensate/ Fractionator Bottoms Exchanger E-101 (33 to 64℃). Then, the feedstock is further pre-heated in the Condensate/TPA Exchanger E-102 (64 to 124℃).

Condensate Fractionator C-101 distills the feedstock into a wild naphtha overhead, kerosene middle and diesel bottoms product. The fractionator is furnished with a top pump around reflux system which form part of the condensate pre-heat train. Kerosene draw from C-101 has light hydrocarbons which are removed by steam stripping in Kerosene Stripper C-102. It is then cooled down by E-100 and then by Kerosene Cooler E-108 before it is pumped on to storage. The C-101 bottom product is cooled down by E-101 and then by Diesel Cooler E-109 before sending to storage.

The wild naphtha overhead liquid is pumped by Stabilizer Feed Pump P-100 via the Feed/Heavy Naphtha Exchanger E-103 (42 to 63℃) and then Feed Exchanger E-104 (63 to 80℃) into Naphtha Stabilizer C-103. C-103 fractionates wild naphtha into overhead product consisting of LPG and column bottom composing of PCN goes to Naphtha Splitter C-104. LPG is cooled down by LPG cooler before sending to storage.

Naphtha bottom from C-103 flows under its own pressure to C-104 where light naphtha and heavy naphtha are separated. The light naphtha is then pumped to storage using Splitter Reflux Pump P-103 after being cooled to 40℃ by Light Naphtha Cooler E-106. The C-104 bottom is heavy naphtha. Heavy Naphtha Pump P-104 boosts the fluid to the required pressure to send it through E-103 and Heavy Naphtha Cooler E-107 before being routed to storage.

3.3.4.3 Process Flow Diagram (PFD) of CFU

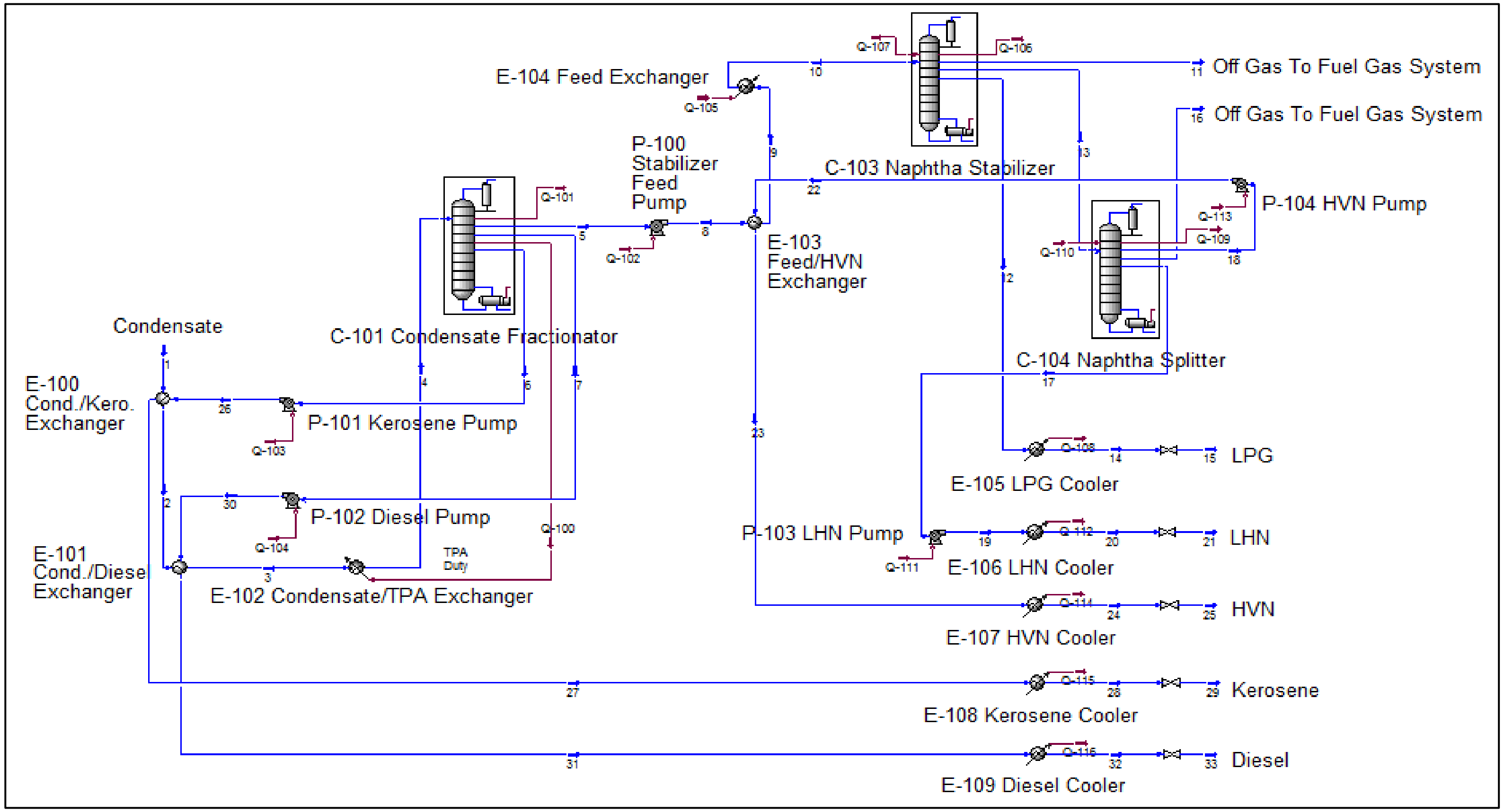

Figure 3-2: CFU model in HYSYS environment.

3.3.4.4 Simulation Base Case and Products Specifications of CFU

Table 3.5 shows the highlights of the important product streams of CFU base case in term of the operating parameters such as temperature, pressure and production flow rates. The outputs of the base case study are compared with the one from PPTSB and relatively small deviations are obtained. Apart from that, the products specifications are compared with the American Society for Testing and Materials (ASTM) Standards and the results are tabulated in **Table 3.6**. The product specifications of the simulated result fall within the acceptable range of the ASTM and PPTSB Standards.

Table 3-7: Highlights of CFU Base Case Study.

Product Stream	**Parameter**	**HYSYS**	**Actual**	**Deviation (%)**
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
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
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
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

Table 3-8: Products Specifications based on ASTM Standards.

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

3.3.5 Conduct the Experiment

In order to measure and study the simultaneous effects of all the 9 controllable factors under the influences of the 2 noise factors towards the objective function, Case Study function in the HYSYS DataBook is used. It enables the selection of both the independent and dependent variables for the HYSYS simulations based on the cross-orthogonal arrays design. **Figure 3.3** and **3.4** below show the screenshots of the Case Study function of HYSYS.

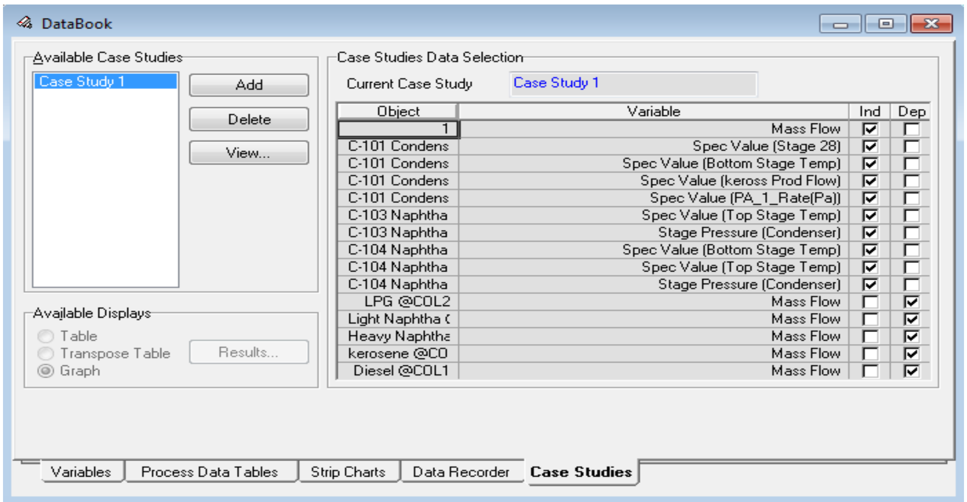

Figure 3-3: HYSYS Case Study (selection of independent and dependent variables).

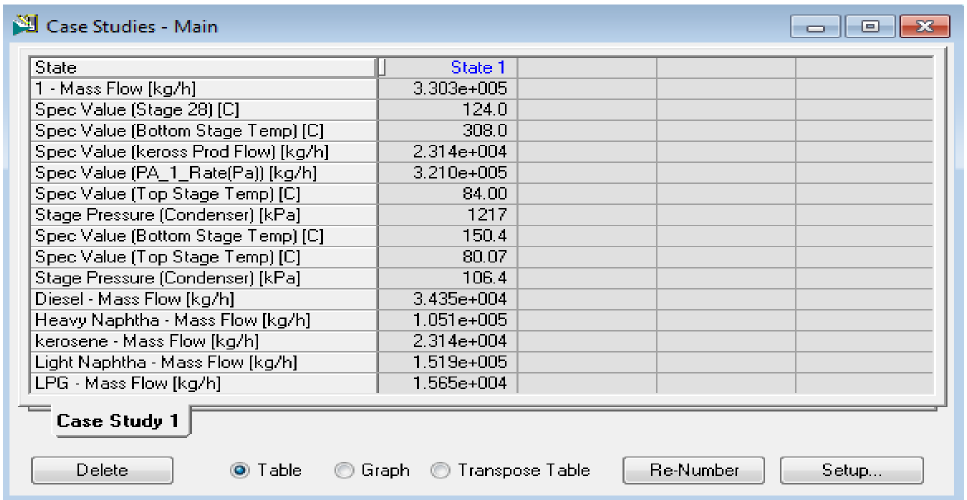

Figure 3-4: HYSYS Case Study (output in production flow rates).

3.4 Statistical Analysis

3.4.1 Nomenclature

Table 3.9 shows the descriptions of the nomenclatures used throughout the current project work.

Table 3-9: Nomenclature

Symbol	Description
C_k^m	Percentage contribution of factor k in Case m (%)
E	Amount of expenses (RM/hour)
E^m	Percentage error for Case m (%)
K	No. of factors
L	No. of levels
N	No. of experiment runs (internal array)
M	No. of experiment runs (external array)
N_R	No. of repeated level
P	Amount of profit (RM/hour)
R	Amount of revenue (RM/hour)
R_k	Ranking of factor k
RM	Ringgit Malaysia
V_k^m	Variance of factor k in Case m [(RM/hour)^2]
$\bar{x}^m$	Average of profit: Case m (RM/hour)
$\bar{x}_{kl}^m$	Average of profit: factor k at level l in Case m (RM/hour)
$\bar{x}_k^m$	Average of profit: factor k at all levels L in each Case m (RM/hour)
x_{opt}^m	Amount of optimum profit in Case m (RM/hour)

3.4.2 Signal-to-Noise Ratio (SNR) Analysis

SNR for each Run n is defined as:

$$(SNR)^n = -10log(MSD)^n \qquad (2)$$

where N=27 is the number of experiment runs in the internal array. As the CFU profit is chosen as the ultimate objective function in the current study, the mean squared deviation (MSD) is defined to uphold "the-larger-the-better" quality principle as follows:

$$(MSD)^n = \frac{1}{M}\sum_{m=1}^{M}\frac{1}{(x^{mn})^2} \qquad (3)$$

where M=9 is the number of experiment runs in the external array.

3.4.3 Analysis of Mean (ANOM) and Analysis of Variance (ANOVA)

Two average values namely the average of factor k at level l in Case m, $\bar{x}_{kl}^{m}$ and the average of factor k over all levels l in each Case m, $\bar{x}_{k}^{m}$ must be calculated during the ANOM and ANOVA.

$$\bar{x}_{kl}^{m} = \frac{1}{N_R}\sum_{n=1}^{N_R} x_{kl}^{mn} \qquad (4)$$

where N_R = 9, K = 9 and L = 3 are correspondingly the number of repeated levels, controllable factors and levels.

$$\bar{x}_{k}^{m} = \frac{1}{L}\sum_{l=1}^{L} \bar{x}_{kl}^{m} \qquad (5)$$

$\bar{x}_{kl}^{m}$ and $\bar{x}_{k}^{m}$ will be used to calculate the variance, V_k^m. The denominator is called the degrees of freedom of factor k over all levels l in Case m,$(DOF)_k^m$ and V_k^m can be calculated as follows:

$$V_k^m = \frac{\sum_{l=1}^{L}(\bar{x}_{kl}^{m} - \bar{x}_{k}^{m})^2}{L_k^m - 1} \quad (6)$$

In ANOVA, the percentage contribution C_k^m can be calculated through the following formula:

$$C_k^m = \frac{100V_k^m}{\sum_{k=1}^{K} V_k^m} \quad (7)$$

3.4.4 Validation of Experiment

In the present work, out of the 243 experiments conducted based on the crossed-orthogonal arrays of L_{27} and L_9, only one run will yield the highest profit margin. A response plot constructed from the average values of profit and SNR of factor k at levels $l = 1, 2$ and 3 against the corresponding controllable factors can be used to determine the optimal configuration of factors contributing towards the highest profit margin. In addition, it can also provide preliminary visual assessment of trends for the average contributions of each controllable factors at all levels.

Optimum profit in Case m, x_{opt}^{m} is calculated through the 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, $\bar{x}_{k}^{m}$ (Yusoff, N. et al., 2011). Additional 9 runs of experiments are required to compare the experimental and calculated values of profit at optimum configuration.

$$x_{opt}^{m} = \bar{x}^m + \left(\sum_{k=1}^{K} \max(\bar{x}_{kl}^{m}) - \bar{x}_{k}^{m}\right) \quad (8)$$

3.5 Gantt-Charts and Key Milestones

Table 3-10: Gantt-Chart of FYP 1.

Task Name	Duration (weeks)	Week														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selection of Project Topic	2															
Preliminary Research Work (Literature Study)																
Fundamental/Application of Taguchi Method	3															
Process Flow of CFU	3															
Taguchi's DOE: Parametric Design	3															
ASPEN HYSYS Simulation	3															
Problem Formulation																
Identification of Objective Function	2															
Identification of Factors and Levels	2															
Experimental Design																
Taguchi's Orthogonal Array	3															
CFU Modeling using Aspen HYSYS	6															
Experimentation/Simulation – First Stage	4															
Key Milestones							A		B					C	D	

A – Submission of Extended Proposal
B – Proposal Defense
C – Submission of Interim Draft Report
D – Submission of Interim Report

Table 3-11: Gantt-Chart of FYP 2.

Task Name	Duration (weeks)	Week 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Conduct Experiment (HYSYS)																
Taguchi Crossed-Orthogonal Array (OA)																
Data Gathering																
Analysis of Results																
Effects of Noise Factors																
Signal-to-Noise Ratio (SNR) Analysis																
Analysis of Means (ANOM)																
Analysis of Variance (ANOVA)																
Validation of Experiment																
Identification of Optimal Configuration																
Verification of Optimum CFU Profit																
Key Milestones							**A**			**B**		**C**		**D**	**E**

A – Submission of Progress Report
B – Pre-SEDEX
C – Submission of Dissertation (soft bound) and Technical Paper
D – Oral Presentation
E – Submission of Project Dissertation (hard bound)

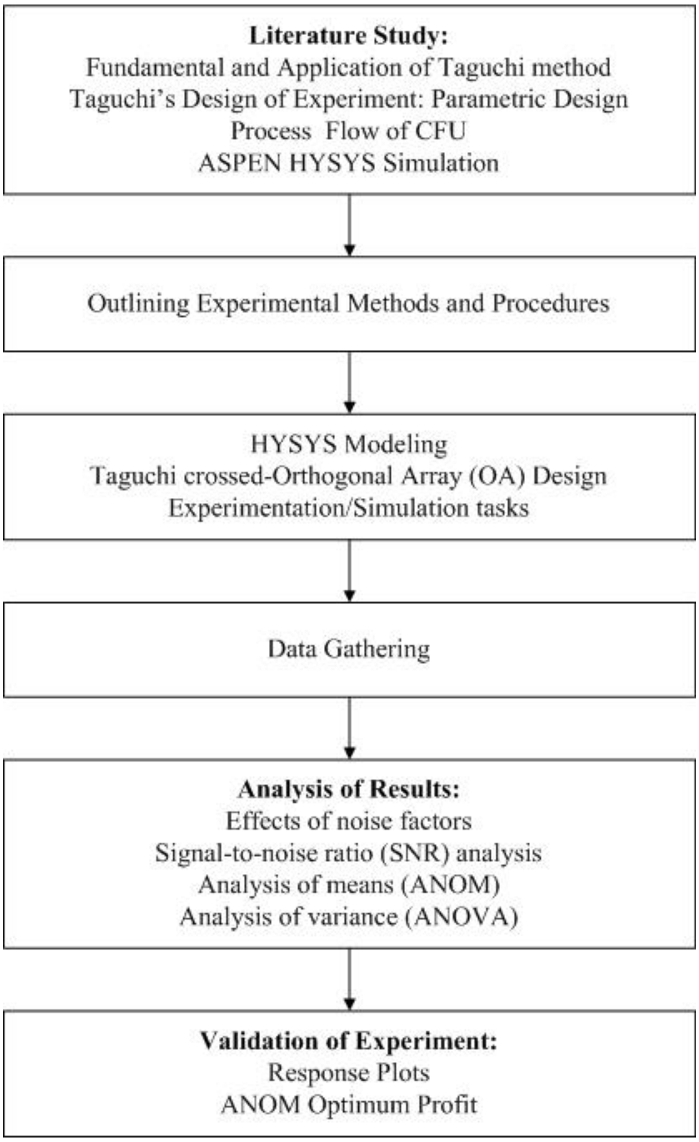

Figure 3-5: Project Key Milestones.

CHAPTER 4

RESULTS AND DISCUSSION

4 RESULTS AND DISCUSSION

4.1 Results of Taguchi Crossed-Orthogonal Array Experiments

All the experiments are conducted using the CFU steady-state model developed under the HYSYS environment. The output of the experiments is in term of production flow rates of the products, namely LPG, LHN, HVN, kerosene and diesel. The objective function (Eq. (1)) is employed to obtain the profit value.

Major results of crossed-orthogonal arrays are tabulated in **Table 4.1** to **4.9**. The summary of the results is shown in **Table 4.10**. The profit is denoted as x^{mn} where m $(m = 1, \ldots, 9)$ and n $(n = 1, \ldots, 27)$ represent the external and internal runs, respectively. Cases 1 – 9 refer to the corresponding values of index m and they are further categorized as Group I (cases 1 – 3), Group II (cases 4 – 6) and Group III (cases 7 – 9) in the following discussion due to their similarity in term of noise factors configuration (factor *J* and *K*).

4.1.1 Case m=1

Table 4-1: Results of Taguchi Cross-Orthogonal Arrays - Case m=1.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	15653	151876	105068	23139	34348	137272	28157	109115
2	15790	154067	102740	25711	31774	138508	29501	109006
3	15988	154340	102268	23139	34348	137435	26674	110761
4	16312	151950	104336	25710	31775	138203	31276	106927
5	16498	152113	103986	23138	34348	137123	28395	108728
6	16312	156897	99389	23140	34346	137610	30213	107397
7	15790	154284	102524	28281	29204	139587	28936	110650
8	16498	157179	98921	25711	31774	138658	28093	110565
9	16129	152823	103644	23139	34348	137264	26402	110862
10	15442	156674	100481	23140	34346	137764	30013	107751
11	15442	156870	100286	25710	31775	138841	29386	109455
12	16188	154551	101859	25710	31775	138473	29026	109447
13	15854	155528	101215	25710	31777	138632	27282	111350
14	16129	153014	103454	25710	31777	138340	26546	111794
15	15653	152101	104844	25711	31774	138351	28301	110050
16	15988	154148	102461	28280	29206	139533	26997	112536
17	16188	154748	101662	28282	29203	139550	29286	110264
18	15442	151616	105541	28282	29203	139406	30276	109130
19	15653	157127	99818	28281	29204	139882	27446	112435
20	16312	156708	99578	28282	29203	139710	29876	109834
21	16129	153236	103232	28280	29206	139420	26698	112722
22	15854	155717	101027	28280	29206	139709	27409	112299
23	16498	151874	104226	28281	29204	139217	28113	111105
24	16188	149598	106811	23140	34346	136949	30121	106828
25	15790	159217	97590	23138	34348	137933	28279	109654
26	15988	154564	102045	25710	31777	138515	26813	111701
27	15854	155939	100803	23139	34348	137613	27063	110550

4.1.2 Case m=2

Table 4-2: Results of Taguchi Cross-Orthogonal Arrays - Case m=2.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	15653	151876	105068	23139	34348	114149	28157	85992
2	15790	154067	102740	25711	31774	115384	29501	85883
3	15988	154340	102268	23139	34348	114312	26674	87638
4	16312	151950	104336	25710	31775	115080	31276	83803
5	16498	152113	103986	23138	34348	113999	28395	85604
6	16312	156897	99389	23140	34346	114487	30213	84274
7	15790	154284	102524	28281	29204	116463	28936	87527
8	16498	157179	98921	25711	31774	115534	28093	87441
9	16129	152823	103644	23139	34348	114140	26402	87738
10	15442	156674	100481	23140	34346	114641	30013	84628
11	15442	156870	100286	25710	31775	115718	29386	86331
12	16188	154551	101859	25710	31775	115349	29026	86323
13	15854	155528	101215	25710	31777	115508	27282	88226
14	16129	153014	103454	25710	31777	115216	26546	88671
15	15653	152101	104844	25711	31774	115227	28301	86926
16	15988	154148	102461	28280	29206	116410	26997	89413
17	16188	154748	101662	28282	29203	116427	29286	87141
18	15442	151616	105541	28282	29203	116282	30276	86007
19	15653	157127	99818	28281	29204	116758	27446	89312
20	16312	156708	99578	28282	29203	116586	29876	86710
21	16129	153236	103232	28280	29206	116296	26698	89598
22	15854	155717	101027	28280	29206	116585	27409	89176
23	16498	151874	104226	28281	29204	116094	28113	87981
24	16188	149598	106811	23140	34346	113825	30121	83704
25	15790	159217	97590	23138	34348	114809	28279	86531
26	15988	154564	102045	25710	31777	115391	26813	88577
27	15854	155939	100803	23139	34348	114490	27063	87427

4.1.3 Case m=3

Table 4-3: Results of Taguchi Cross-Orthogonal Arrays - Case m=3.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	15653	151876	105068	23139	34348	91025	28157	62868
2	15790	154067	102740	25711	31774	92260	29501	62759
3	15988	154340	102268	23139	34348	91188	26674	64514
4	16312	151950	104336	25710	31775	91956	31276	60680
5	16498	152113	103986	23138	34348	90875	28395	62481
6	16312	156897	99389	23140	34346	91363	30213	61150
7	15790	154284	102524	28281	29204	93339	28936	64403
8	16498	157179	98921	25711	31774	92411	28093	64318
9	16129	152823	103644	23139	34348	91016	26402	64614
10	15442	156674	100481	23140	34346	91517	30013	61504
11	15442	156870	100286	25710	31775	92594	29386	63208
12	16188	154551	101859	25710	31775	92225	29026	63200
13	15854	155528	101215	25710	31777	92385	27282	65103
14	16129	153014	103454	25710	31777	92093	26546	65547
15	15653	152101	104844	25711	31774	92103	28301	63803
16	15988	154148	102461	28280	29206	93286	26997	66289
17	16188	154748	101662	28282	29203	93303	29286	64017
18	15442	151616	105541	28282	29203	93159	30276	62883
19	15653	157127	99818	28281	29204	93634	27446	66188
20	16312	156708	99578	28282	29203	93462	29876	63586
21	16129	153236	103232	28280	29206	93172	26698	66475
22	15854	155717	101027	28280	29206	93461	27409	66052
23	16498	151874	104226	28281	29204	92970	28113	64857
24	16188	149598	106811	23140	34346	90701	30121	60580
25	15790	159217	97590	23138	34348	91686	28279	63407
26	15988	154564	102045	25710	31777	92267	26813	65454
27	15854	155939	100803	23139	34348	91366	27063	64303

4.1.4 Case m=4

Table 4-4: Results of Taguchi Cross-Orthogonal Arrays - Case m=4.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	16483	159879	110595	23138	37374	144029	29766	114263
2	16627	162181	108151	25711	34800	145276	31174	114102
3	16836	162484	107636	23140	37373	144205	28242	115963
4	17176	159957	109826	25709	34801	144956	33033	111923
5	17372	160128	109457	23138	37374	143874	30017	113857
6	17176	165164	104618	23140	37372	144388	31888	112500
7	16627	162413	107918	28281	32230	146356	30567	115789
8	17372	165461	104125	25711	34800	145435	29690	115745
9	16983	160875	109097	23140	37373	144023	27953	116070
10	16260	164929	105768	23140	37372	144550	31678	112872
11	16260	165135	105563	25709	34801	145627	31044	114584
12	17046	162694	107219	25709	34801	145239	30664	114575
13	16694	163723	106541	25710	34802	145407	28872	116535
14	16983	161075	108898	25710	34802	145100	28097	117003
15	16483	160115	110361	25711	34800	145111	29909	115202
16	16835	162271	107851	28280	32231	146300	28550	117751
17	17046	162901	107012	28282	32228	146318	30880	115438
18	16260	159604	111095	28282	32228	146166	31922	114244
19	16483	165406	105070	28281	32230	146667	28999	117667
20	17176	164964	104818	28282	32228	146486	31501	114984
21	16983	161310	108664	28280	32231	146181	28235	117946
22	16694	163917	106347	28280	32231	146484	28983	117501
23	17372	159876	109711	28281	32230	145968	29701	116267
24	17046	157481	112431	23140	37372	143691	31792	111899
25	16627	167606	102724	23138	37374	144727	29895	114832
26	16835	162707	107414	25710	34802	145284	28379	116905
27	16694	164155	106107	23140	37373	144391	28649	115742

4.1.5 Case m=5

Table 4-5: Results of Taguchi Cross-Orthogonal Arrays - Case m=5.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	16483	159879	110595	23138	37374	119689	29766	89923
2	16627	162181	108151	25711	34800	120935	31174	89762
3	16836	162484	107636	23140	37373	119864	28242	91622
4	17176	159957	109826	25709	34801	120615	33033	87582
5	17372	160128	109457	23138	37374	119534	30017	89517
6	17176	165164	104618	23140	37372	120047	31888	88159
7	16627	162413	107918	28281	32230	122016	30567	91449
8	17372	165461	104125	25711	34800	121094	29690	91404
9	16983	160875	109097	23140	37373	119682	27953	91729
10	16260	164929	105768	23140	37372	120209	31678	88531
11	16260	165135	105563	25709	34801	121287	31044	90243
12	17046	162694	107219	25709	34801	120898	30664	90234
13	16694	163723	106541	25710	34802	121067	28872	92194
14	16983	161075	108898	25710	34802	120759	28097	92662
15	16483	160115	110361	25711	34800	120770	29909	90862
16	16835	162271	107851	28280	32231	121960	28550	93410
17	17046	162901	107012	28282	32228	121978	30880	91097
18	16260	159604	111095	28282	32228	121825	31922	89903
19	16483	165406	105070	28281	32230	122326	28999	93327
20	17176	164964	104818	28282	32228	122145	31501	90644
21	16983	161310	108664	28280	32231	121840	28235	93605
22	16694	163917	106347	28280	32231	122144	28983	93161
23	17372	159876	109711	28281	32230	121627	29701	91926
24	17046	157481	112431	23140	37372	119350	31792	87559
25	16627	167606	102724	23138	37374	120387	29895	90492
26	16835	162707	107414	25710	34802	120943	28379	92564
27	16694	164155	106107	23140	37373	120050	28649	91401

4.1.6 Case m=6

Table 4-6: Results of Taguchi Cross-Orthogonal Arrays - Case m=6.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	16483	159879	110595	23138	37374	95348	29766	65582
2	16627	162181	108151	25711	34800	96595	31174	65421
3	16836	162484	107636	23140	37373	95523	28242	67281
4	17176	159957	109826	25709	34801	96274	33033	63241
5	17372	160128	109457	23138	37374	95193	30017	65176
6	17176	165164	104618	23140	37372	95706	31888	63818
7	16627	162413	107918	28281	32230	97675	30567	67108
8	17372	165461	104125	25711	34800	96753	29690	67063
9	16983	160875	109097	23140	37373	95342	27953	67389
10	16260	164929	105768	23140	37372	95868	31678	64191
11	16260	165135	105563	25709	34801	96946	31044	65902
12	17046	162694	107219	25709	34801	96558	30664	65894
13	16694	163723	106541	25710	34802	96726	28872	67854
14	16983	161075	108898	25710	34802	96418	28097	68321
15	16483	160115	110361	25711	34800	96430	29909	66521
16	16835	162271	107851	28280	32231	97619	28550	69069
17	17046	162901	107012	28282	32228	97637	30880	66756
18	16260	159604	111095	28282	32228	97485	31922	65563
19	16483	165406	105070	28281	32230	97985	28999	68986
20	17176	164964	104818	28282	32228	97804	31501	66303
21	16983	161310	108664	28280	32231	97499	28235	69264
22	16694	163917	106347	28280	32231	97803	28983	68820
23	17372	159876	109711	28281	32230	97286	29701	67585
24	17046	157481	112431	23140	37372	95010	31792	63218
25	16627	167606	102724	23138	37374	96046	29895	66151
26	16835	162707	107414	25710	34802	96602	28379	68223
27	16694	164155	106107	23140	37373	95710	28649	67061

4.1.7 Case m=7

Table 4-7: Results of Taguchi Cross-Orthogonal Arrays - Case m=7.

Run	**LPG**	**LHN**	**HVN**	**Kero**	**Diesel**	**Profit before Utility**	**Utility Cost**	**Profit after Utility**
						(RM/hour)		
1	17312	167881	116123	23137	40402	150789	31375	119414
2	17464	170302	113552	25712	37825	152046	32843	119203
3	17683	170604	113027	23140	40401	150973	29803	121170
4	18041	167954	115325	25709	37827	151708	34791	116917
5	18246	168142	114928	23137	40402	150626	31638	118988
6	18041	173430	109846	23140	40398	151166	33562	117603
7	17464	170542	113313	28281	35255	153127	32227	120900
8	18246	173742	109330	25712	37825	152213	31287	120925
9	17838	168927	114549	23140	40401	150783	29502	121281
10	17079	173184	111054	23140	40398	151336	33341	117995
11	17079	173400	110841	25709	37827	152414	32700	119714
12	17904	170837	112578	25709	37827	152007	32301	119705
13	17534	171917	111866	25710	37829	152183	30462	121721
14	17838	169138	114341	25710	37829	151861	29648	122212
15	17312	168129	115877	25712	37825	151873	31516	120356
16	17683	170394	113241	28280	35257	153068	30118	122950
17	17904	171054	112362	28282	35254	153087	32518	120569
18	17079	167592	116648	28282	35254	152927	33611	119316
19	17312	173684	110322	28281	35255	153453	30582	122871
20	18040	173220	110059	28282	35254	153263	33170	120093
21	17838	169384	114096	28280	35257	152942	29788	123155
22	17534	172126	111658	28280	35257	153262	30573	122688
23	18246	167878	115195	28281	35255	152719	31318	121401
24	17904	165363	118050	23140	40398	150434	33461	116974
25	17464	175994	107857	23137	40402	151522	31510	120012
26	17683	170851	112784	25710	37829	152054	29944	122109
27	17534	172371	111409	23140	40401	151169	30233	120937

4.1.8 Case m=8

Table 4-8: Results of Taguchi Cross-Orthogonal Arrays - Case m=8.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	17312	167881	116123	23137	40402	125232	31375	93856
2	17464	170302	113552	25712	37825	126489	32843	93646
3	17683	170604	113027	23140	40401	125415	29803	95612
4	18041	167954	115325	25709	37827	126150	34791	91360
5	18246	168142	114928	23137	40402	125069	31638	93430
6	18041	173430	109846	23140	40398	125608	33562	92046
7	17464	170542	113313	28281	35255	127569	32227	95342
8	18246	173742	109330	25712	37825	126655	31287	95368
9	17838	168927	114549	23140	40401	125225	29502	95723
10	17079	173184	111054	23140	40398	125778	33341	92437
11	17079	173400	110841	25709	37827	126856	32700	94157
12	17904	170837	112578	25709	37827	126449	32301	94148
13	17534	171917	111866	25710	37829	126626	30462	96164
14	17838	169138	114341	25710	37829	126303	29648	96655
15	17312	168129	115877	25712	37825	126315	31516	94798
16	17683	170394	113241	28280	35257	127510	30118	97393
17	17904	171054	112362	28282	35254	127529	32518	95011
18	17079	167592	116648	28282	35254	127369	33611	93758
19	17312	173684	110322	28281	35255	127895	30582	97314
20	18040	173220	110059	28282	35254	127705	33170	94535
21	17838	169384	114096	28280	35257	127385	29788	97597
22	17534	172126	111658	28280	35257	127704	30573	97130
23	18246	167878	115195	28281	35255	127161	31318	95843
24	17904	165363	118050	23140	40398	124877	33461	91416
25	17464	175994	107857	23137	40402	125964	31510	94454
26	17683	170851	112784	25710	37829	126496	29944	96551
27	17534	172371	111409	23140	40401	125612	30233	95379

4.1.9 Case m=9

Table 4-9: Results of Taguchi Cross-Orthogonal Arrays - Case m=9.

Run	LPG	LHN	HVN	Kero	Diesel	Profit before Utility	Utility Cost	Profit after Utility
						(RM/hour)		
1	17312	167881	116123	23137	40402	99674	31375	68299
2	17464	170302	113552	25712	37825	100931	32843	68088
3	17683	170604	113027	23140	40401	99857	29803	70055
4	18041	167954	115325	25709	37827	100593	34791	65802
5	18246	168142	114928	23137	40402	99511	31638	67873
6	18041	173430	109846	23140	40398	100050	33562	66488
7	17464	170542	113313	28281	35255	102011	32227	69784
8	18246	173742	109330	25712	37825	101097	31287	69810
9	17838	168927	114549	23140	40401	99668	29502	70166
10	17079	173184	111054	23140	40398	100220	33341	66880
11	17079	173400	110841	25709	37827	101299	32700	68599
12	17904	170837	112578	25709	37827	100891	32301	68590
13	17534	171917	111866	25710	37829	101068	30462	70606
14	17838	169138	114341	25710	37829	100745	29648	71097
15	17312	168129	115877	25712	37825	100757	31516	69241
16	17683	170394	113241	28280	35257	101953	30118	71835
17	17904	171054	112362	28282	35254	101971	32518	69454
18	17079	167592	116648	28282	35254	101812	33611	68201
19	17312	173684	110322	28281	35255	102337	30582	71756
20	18040	173220	110059	28282	35254	102147	33170	68978
21	17838	169384	114096	28280	35257	101827	29788	72039
22	17534	172126	111658	28280	35257	102146	30573	71573
23	18246	167878	115195	28281	35255	101603	31318	70285
24	17904	165363	118050	23140	40398	99319	33461	65858
25	17464	175994	107857	23137	40402	100407	31510	68897
26	17683	170851	112784	25710	37829	100938	29944	70994
27	17534	172371	111409	23140	40401	100054	30233	69821

Table 4-10: Summary of Results of Taguchi Crossed-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}	$\overline{x}^{n}$
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 internal array.

4.2 Effect of Noise Factors

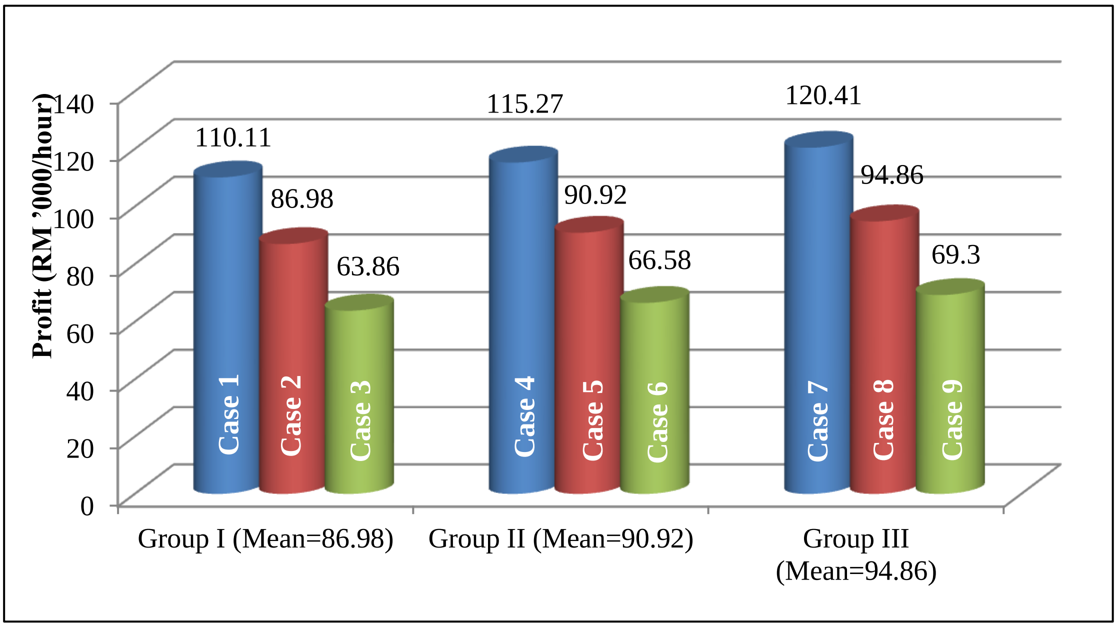

Figure 4-1: Effects of Noise Factors.

Figure 4.1 presents the effects of noise factors towards the objective function in the graphical form. Global means for Cases 1, 2 and 3 (Group I) are 110108, 86984 and 63860 RM/hour. For Cases 4, 5 and 6 (Group II), the global means are 115265, 90924 and 66583 RM/hour whereas the global means for Cases 7, 8 and 9 (Group III) are 120414, 94856 and 69298 RM/hour, respectively. Means for Group I, II and III are 86984, 90924 and 94856 RM/hour, respectively. It is noteworthy that a difference of about 4000 RM/hour is noticed between Groups I and II and between Groups II and III.

This discrepancy is caused by the presence of noise factor *J*, which is the plant load. The amount of condensate feed increases when the plant load is increased, which further contribute towards a greater CFU profit due to the additional production of LPG, LHN, HVN, Kerosene and Diesel products. Nevertheless, a higher amount of condensate feed will push the equipment loads towards the upper constraints whereas under loading is undesirable as the CFU profit will decrease and the fractionation operation will become economically unfeasible.

On the other hand, the effect of noise factor *K*, which is the condensate feed price can also be deduced. It is noteworthy that the highest values of average profit in each Groups I, II and III are generated from K_1 (factor *K*, level 1) configuration. In cases 1, 4 and 7, the average profits are, respectively, 110108, 115265 and 120414 RM/hour. This is due to the different economic values of the condensate feed. Highly priced condensate feed decreases the CFU profit while the cheaper one increases it.

4.3 Averaged Profit Analysis

For the CFU averaged profit analysis, means values of profit from Cases 1 to 9 are calculated in a row-by-row basis. The means profits are denoted as $\bar{x}^n$ where the superscript n is the runs of experiment in the internal array. Ranking of controllable factors can be performed using the ANOM in which the significance of factors can be measured quantitatively. Eq. (4) and eq. (5) are employed in order to calculate the averages of factors *k*. The highest ranking is given to a factor with the highest deviation, E_k value. In the case of 9 controllable factors that influence the CFU profit, the order of importance in a descending sequence is *ACHIGDFBE*. This indicates that factor *A* is the most significant while factor *E* is the least significant. Results of ANOM are presented in **Table 4.11**.

Ranking from ANOM is verified with ranking from ANOVA. Percentage contribution, C_k^m calculated from variance, V_k^m is used to determine the significance of factors. A factor with the highest value of C_k^m is the most important factor. Ranking of factors based on ANOVA is presented in **Table 4.12**. The descending order of importance of the 9 controllable factors is *ACHIGDFEB*. The results are found similar to the one obtained from ANOM except for the last two factors, in which *E* and *B* switch places.

Table 4-11: Analysis of Means (ANOM) for Average Profit.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	92.48	90.93	89.88	91.05	90.93	90.80	91.22	90.44	91.33
$l = 2$	90.96	90.93	90.83	91.00	90.90	90.91	91.01	90.96	90.95
$l = 3$	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

Note: Average profit values are presented in the unit of RM ’000/hour.

Table 4-12: Analysis of Variance (ANOVA) for Average Profit.

	Controllable Factors								
	A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***
$(DOF)_k$	2	2	2	2	2	2	2	2	2
V_k	2.5E+6	1.9E+2	1.2E+6	3.3E+4	5.3E+2	1.7E+4	1.2E+5	2.1E+5	1.8E+5
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 of ANOM and ANOVA indicate that factors *A*, *C*, *H*, *I* and *G* are contributing to the maximization of CFU profit. The results are presented in **Figure 4.2** in term of percentage contribution of controllable factors. Factor *A* (58.9%) deals with the controlling of C-101 top-stage temperature in which it affects the rate of production of wild naphtha, kerosene and diesel. Effect of factor *C* is also significant with 27.8% contribution. It deals with the kerosene flow rate constraint. Kerosene has the highest economic value among the 5 refined products. An increase in factor *C* increases the kerosene production which further contributing towards a higher profit.

Factor *H*, *I* and *G* has a contribution of 5.1%, 4.1% and 2.9%, respectively. 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. In contrast, the effects of factor *B*, *D*, *E* and *F* are found trivial with a percentage contribution of 0.005%, 0.77%, 0.01% and 0.39%, respectively.

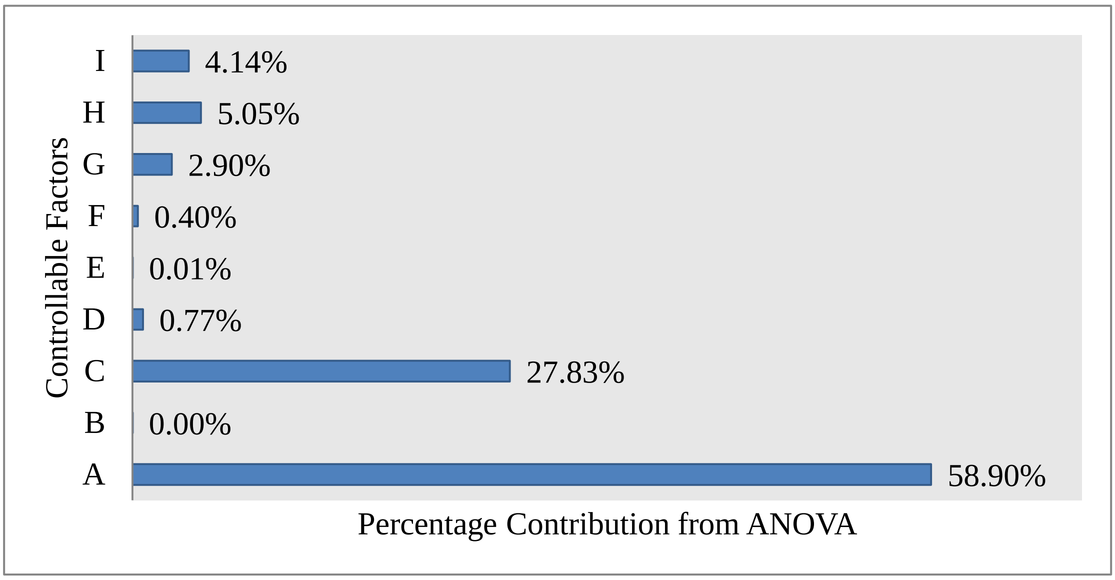

Figure 4-2: Percentage Contribution of Controllable Factors from ANOVA in Averaged Profit Analysis.

4.4 Signal-to-Noise Ratio (SNR) Analysis

Significance of the 9 controllable factors is measured using signal-to-noise ratio (SNR) method and "the-larger-the-better" qualitative principle is used for this analysis. A high SNR value shows the minimum influences of noise factors towards the objective function. The SNR values can be calculated using eq. (2) and eq. (3). The calculated SNR are used to determine the ranking of importance for the controllable factors that can minimize the influences of noise factors. The output of SNR analysis is presented in **Table 4.13**.

Similarly, ANOM and ANOVA are employed in the SNR analysis and the results of ranking are presented in **Table 4.14** and **Table 4.15**, respectively. The results are found identical in which the ranking of factors in the descending order of importance is *ACHIGDFEB*. Factor *A* is the most significant factor while factor *B* is the least important one. It is noteworthy that the ranking orders for statistical analyses using the averaged profit and the SNR values agree markedly. The findings show the consistency of Taguchi method as well as its orthogonal arrays design.

Table 4-13: Results of Signal-to-Noise Ratio (SNR) Analysis.

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

Table 4-14: Analysis of Means (ANOM) for SNR.

	Controllable Factors								
	$\overline{SNR}_{Al}$	$\overline{SNR}_{Bl}$	$\overline{SNR}_{Cl}$	$\overline{SNR}_{Dl}$	$\overline{SNR}_{El}$	$\overline{SNR}_{Fl}$	$\overline{SNR}_{Gl}$	$\overline{SNR}_{Hl}$	$\overline{SNR}_{Il}$
$l = 1$	98.67	98.51	98.39	98.52	98.50	98.49	98.53	98.45	98.55
$l = 2$	98.51	98.50	98.49	98.51	98.50	98.50	98.51	98.51	98.51
$l = 3$	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

Table 4-15: Analysis of Variance (ANOVA) for SNR.

	Controllable Factors								
	A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***
$(\boldsymbol{DOF})_k$	2	2	2	2	2	2	2	2	2
$\boldsymbol{V_k}$	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
$\boldsymbol{C_k}$	58.73	0.01	27.75	0.88	0.02	0.42	2.87	5.10	4.21
$\boldsymbol{R_k}$	1	9	2	6	8	7	5	3	4

Apart from determining the significance of factors towards the stabilization of disturbances, SNR results can be used to identify the optimal configuration of factors yielding the highest CFU profit. The highest SNR value of 98.80 comes from Run 21 with configuration of A_1 B_3 C_3 D_3 E_1 F_1 G_1 H_3 I_3. This unique configuration based on the Taguchi method consistently gives the highest profit values in all Cases 1-9. A profit of 123154 RM/hour from Case 7 is the maximum one found from all the 243 experiments conducted. This result confirms that the SNR principle employed in this study is valid in determining the highest value of the CFU profit.

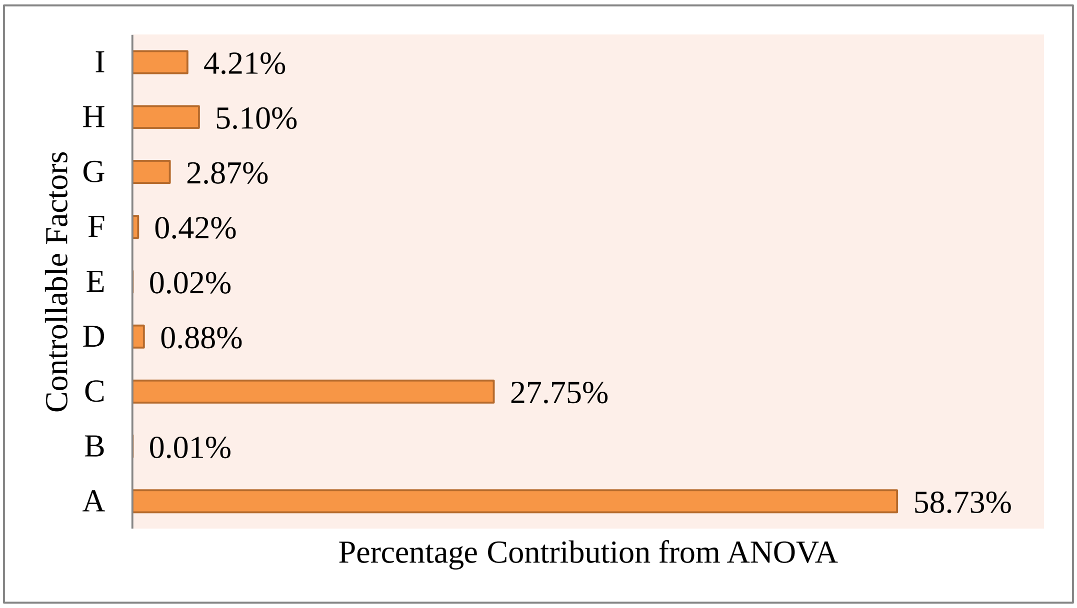

Figure 4-3: Percentage Contribution of Controllable Factors from ANOVA in SNR Analysis.

4.5 Validation of Taguchi's DOE

4.5.1 Response Plot

The final step in the Taguchi method is the validation of results. In the present work, optimal configuration of controllable factors from analyses based on the averaged profit and the SNR values can be determined from two separate response plots (**Figure 4.4** and **4.5**). Two quantitative observations can be made from this response plot.

- Significance of individual factors can be established from the steepness of the response plot slopes
- Levels of individual factors yielding the maximum CFU profits and/or the SNR can be visually determined.

In the first observation, the steeper the slope of the response graph, the more significant the factor is. This deduction can complement the percentage contributions of factors, C_k as discussed in the ANOVA above. The second observation is important in estimating and validating the experimental results. A configuration of optimal level of factors should yield a maximum value of the CFU profit.

In order to compare the outcomes of both the response plots towards the optimal configuration of factors, both the plots are superimposed and shown in **Figure 4.6**. Scrutinized closely, outputs from both the response plots of averaged profit and SNR are strikingly identical. An optimal configuration of $A_1B_1C_3D_1E_3F_3G_1H_3I_1$ is obtained. In general, the maximum and minimum values of profit can only be ascertained after running the entire 19, 683 (3^9) experiments under the full factorial design approach. It is possible that profit values derived from the Taguchi method do not reach either side of the extremities. Hence, it is important to estimate and validate the maximum value of the profit by running another set of experiments under the optimal configuration of both the controllable and noise factors.

In the current work, additional experiments with 9 runs in HYSYS case study are required to compare both the Taguchi experimental and the calculated values of profit suggested by ANOM (section 4.5.2). The implemented results in both production flow rates and profit values are shown in **Table 4.16**.

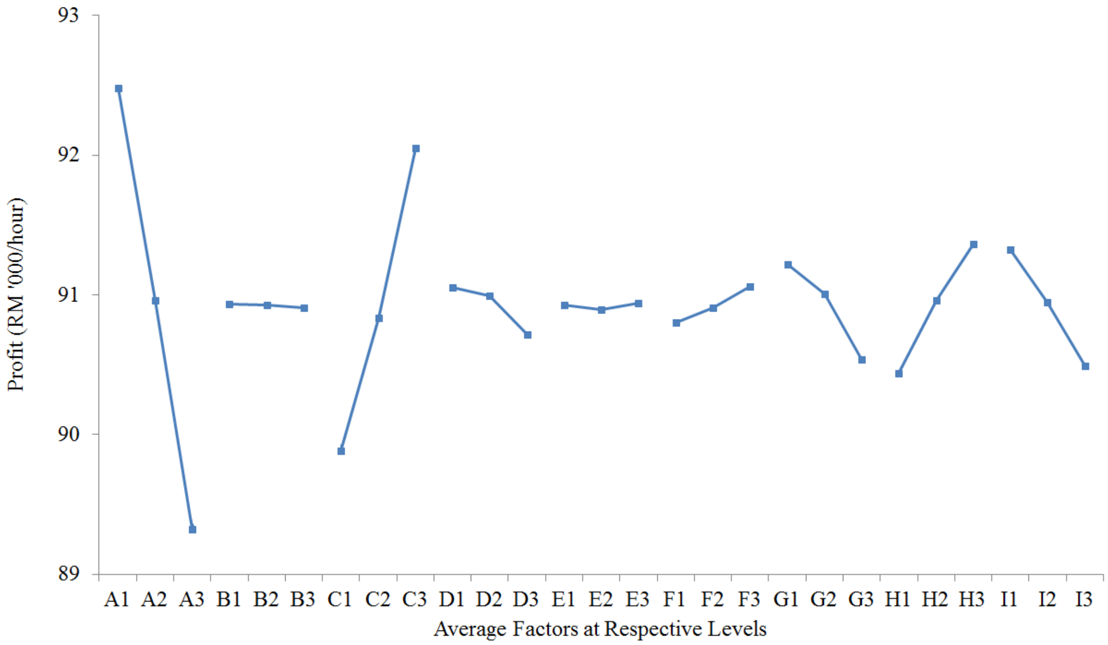

Figure 4-4: Response plot for average profit analysis

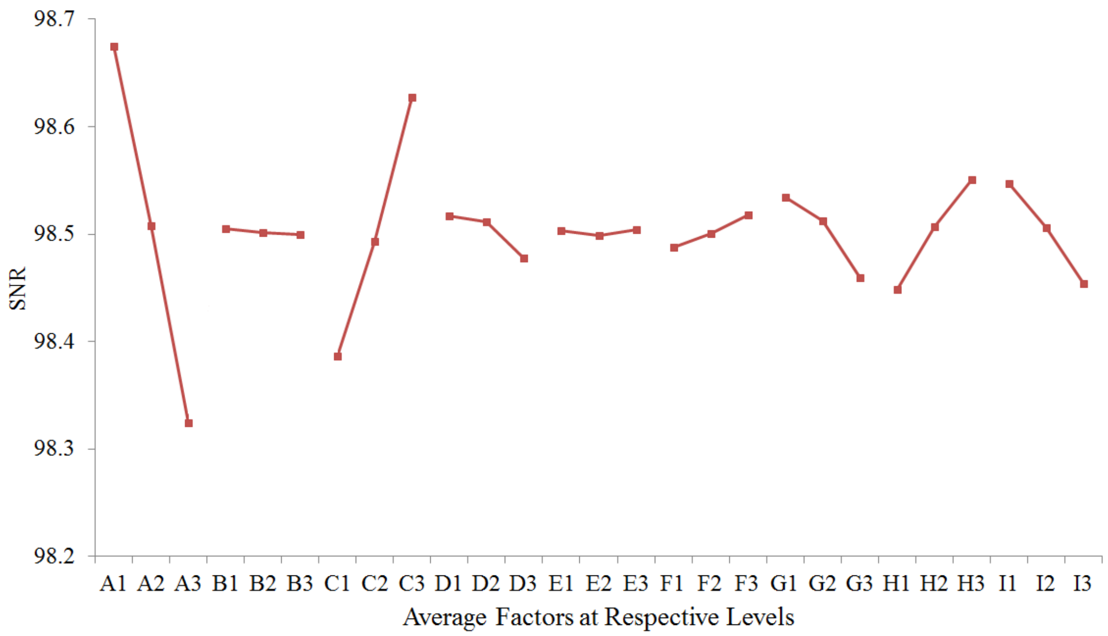

Figure 4-5: Response Plot for SNR Analysis.

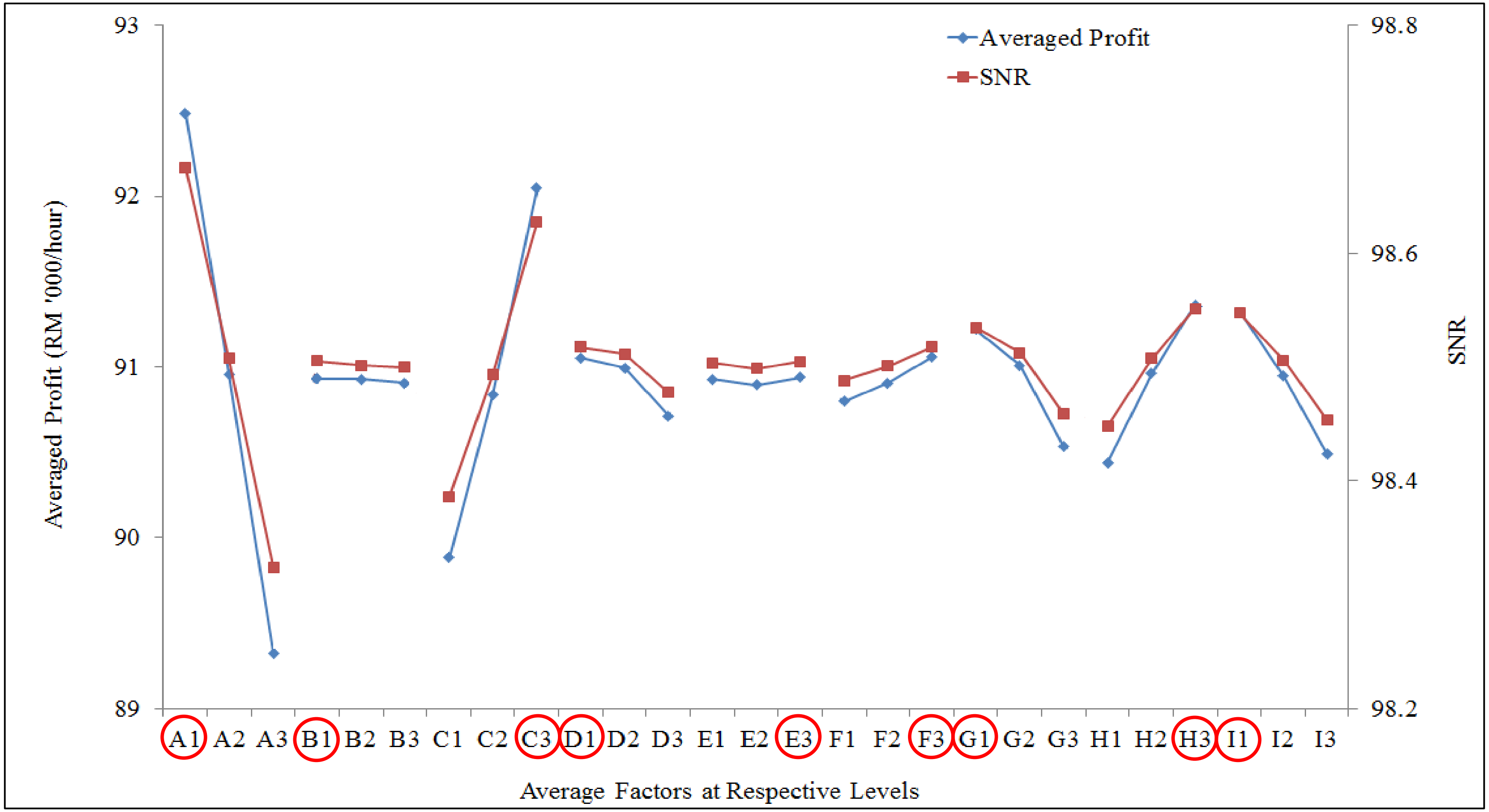

Figure 4-6: The Superimposed Graph of Response Plots.

Table 4-16: Results of Validation Run based on the Outputs of Response Plots.

	Production Mass Flow Rate (kg/hour)					Profit (RM/hour)
	LPG	**LHN**	**HVN**	**Kerosene**	**Diesel**	
Case 1	15853.68	156862.81	99880.56	28280.95	29205.01	113707
Case 2	15853.68	156862.81	99880.56	28280.95	29205.01	90583
Case 3	15853.68	156862.81	99880.56	28280.95	29205.01	67460
Case 4	16693.77	165128.37	105135.35	28280.35	32231.16	118999
Case 5	16693.77	165128.37	105135.35	28280.35	32231.16	94658
Case 6	16693.77	165128.37	105135.35	28280.35	32231.16	70318
Case 7	17533.85	173393.02	110390.97	28280.78	35256.38	124247
Case 8	17533.85	173393.02	110390.97	28280.78	35256.38	98690
Case 9	17533.85	173393.02	110390.97	28280.78	35256.38	73132

4.5.2 ANOM Optimum Profit

The optimum profit values obtained from the validation experiments are compared with the ones calculated from Eq. (8), which are termed ANOM profit values. Eq. (8) contains two quantities, namely, global means and maximum differences of averages of factor k for the corresponding Cases m (1-9). Assuming that HYSYS experimental results based on the validation are the correct ones, the deviation from these values are termed error, E^m for Cases m (1-9). The positive E^m values indicate that HYSYS experimental results are lower than those calculated from ANOM. **Table 4.17** to **4.25** show the optimum profits calculated from ANOM for Cases m (1-9).

4.5.2.1 Case m=1

Table 4-17: ANOM Optimum Profit - Case m=1.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	111.62	110.11	109.07	110.24	110.11	109.99	110.39	109.65	110.49
$l = 2$	110.15	110.11	110.03	110.17	110.08	110.09	110.19	110.15	110.13
$l = 3$	108.56	110.10	111.22	109.91	110.13	110.24	109.74	110.53	109.70
$\bar{x}_k$	110.11	110.11	110.11	110.11	110.11	110.11	110.11	110.11	110.11
D_k	1511.48	5.54	1111.46	135.47	18.09	129.33	282.72	419.04	384.63

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 1 (from Table 4.10) = 110108 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 3998 RM/hour

ANOM Optimum Profit Case 1 = 110108 + 3998 = **114106 RM/hour**

4.5.2.2 Case m=2

Table 4-18: ANOM Optimum Profit - Case m=2.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	88.50	86.99	85.95	87.12	86.99	86.87	87.27	86.53	87.37
$l = 2$	87.02	86.99	86.91	87.05	86.96	86.97	87.07	87.02	87.01
$l = 3$	85.44	86.97	88.10	86.78	87.00	87.11	86.62	87.40	86.57
$\bar{x}_k$	86.98	86.98	86.98	86.98	86.98	86.98	86.98	86.98	86.98
D_k	1511.48	5.54	1111.46	135.47	18.09	129.33	282.72	419.04	384.63

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 2 (from Table 4.10) = 86984 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 3998 RM/hour

ANOM Optimum Profit Case 2 = 86984 + 3998 = **90982 RM/hour**

4.5.2.3 Case m=3

Table 4-19: ANOM Optimum Profit - Case m=3.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	65.37	63.87	62.82	64.00	63.87	63.75	64.14	63.40	64.25
$l = 2$	63.90	63.87	63.79	63.93	63.84	63.85	63.95	63.90	63.89
$l = 3$	62.31	63.85	64.97	63.66	63.88	63.99	63.49	64.28	63.45
$\bar{x}_k$	63.86	63.86	63.86	63.86	63.86	63.86	63.86	63.86	63.86
D_k	1511.48	5.54	1111.46	135.47	18.09	129.33	282.72	419.04	384.63

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 3 (from Table 4.10) = 63860 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 3998 RM/hour

ANOM Optimum Profit Case 3 = 63860 + 3998 = **67858 RM/hour**

4.5.2.4 Case m=4

Table 4-20: ANOM Optimum Profit - Case m=4.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	116.82	115.28	114.22	115.40	115.27	115.14	115.56	114.78	115.67
$l = 2$	115.30	115.27	115.17	115.34	115.24	115.25	115.35	115.31	115.29
$l = 3$	113.67	115.25	116.40	115.06	115.28	115.40	114.88	115.71	114.83
$\bar{x}_k$	115.27	115.27	115.27	115.27	115.27	115.27	115.27	115.27	115.27
D_k	1558.71	11.56	1133.43	132.60	19.26	136.11	297.44	441.23	405.01

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 4 (from Table 4.10) = 115265 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 4135 RM/hour

ANOM Optimum Profit Case 4 = 115625 + 4135 = **119400 RM/hour**

4.5.2.5 Case m=5

Table 4-21: ANOM Optimum Profit - Case m=5.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	92.48	90.94	89.88	91.06	90.93	90.80	91.22	90.44	91.33
$l = 2$	90.96	90.93	90.83	91.00	90.90	90.91	91.01	90.96	90.95
$l = 3$	89.33	90.91	92.06	90.72	90.94	91.06	90.54	91.37	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	1558.71	11.56	1133.43	132.60	19.26	136.11	297.44	441.23	405.01

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 5 (from Table 4.10) = 90924 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^{m}) - \bar{x}_k^m$ = sum of D_k for all cases = 4135 RM/hour

ANOM Optimum Profit Case 5 = 90924 + 4135 = **95059 RM/hour**

4.5.2.6 Case m=6

Table 4-22: ANOM Optimum Profit - Case m=6.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	68.14	66.60	65.54	66.72	66.59	66.46	66.88	66.10	66.99
$l = 2$	66.62	66.59	66.49	66.66	66.56	66.57	66.67	66.62	66.61
$l = 3$	64.99	66.57	67.72	66.38	66.60	66.72	66.20	67.03	66.15
$\bar{x}_k$	66.58	66.58	66.58	66.58	66.58	66.58	66.58	66.58	66.58
D_k	1558.71	11.56	1133.43	132.60	19.26	136.11	297.44	441.23	405.01

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 6 (from Table 4.10) = 66584 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^{m}) - \bar{x}_k^m$ = sum of D_k for all cases = 4135 RM/hour

ANOM Optimum Profit Case 6 = 66584 + 4135 = **70719 RM/hour**

4.5.2.7 Case m=7

Table 4-23: ANOM Optimum Profit - Case m=7.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	122.02	120.43	119.37	120.54	120.42	120.29	120.73	119.91	120.84
$l = 2$	120.45	120.42	120.32	120.49	120.39	120.40	120.51	120.46	120.44
$l = 3$	118.77	120.39	121.55	120.21	120.43	120.56	120.01	120.88	119.96
$\bar{x}_k$	120.41	120.41	120.41	120.41	120.41	120.41	120.41	120.41	120.41
D_k	1610.71	13.73	1135.09	129.94	20.17	142.86	312.26	463.20	425.28

Note: Average profit values are presented in the unit of RM '000/hour.

Global mean $\bar{x}^m$ of Case 7 (from Table 4.10) = 120414 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 4253 RM/hour

ANOM Optimum Profit Case 7 = 120414 + 4253 = **124667 RM/hour**

4.5.2.8 Case m=8

Table 4-24: ANOM Optimum Profit - Case m=8.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l = 1$	96.47	94.87	93.82	94.99	94.86	94.73	95.17	94.35	95.28
$l = 2$	94.89	94.86	94.76	94.94	94.83	94.84	94.95	94.90	94.88
$l = 3$	93.21	94.84	95.99	94.65	94.88	95.00	94.45	95.32	94.40
$\bar{x}_k$	94.86	94.86	94.86	94.86	94.86	94.86	94.86	94.86	94.86
D_k	1610.71	13.73	1135.09	129.94	20.17	142.86	312.26	463.20	425.28

Note: Average profit values are presented in the unit of RM '000/hour.

Global mean $\bar{x}^m$ of Case 8 (from Table 4.10) = 94856 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 4253 RM/hour

ANOM Optimum Profit Case 8 = 94856 + 4253 = **99109 RM/hour**

4.5.2.9 Case m=9

Table 4-25: ANOM Optimum Profit - Case m=9.

	Controllable Factors								
	$\bar{x}_{Al}$	$\bar{x}_{Bl}$	$\bar{x}_{Cl}$	$\bar{x}_{Dl}$	$\bar{x}_{El}$	$\bar{x}_{Fl}$	$\bar{x}_{Gl}$	$\bar{x}_{Hl}$	$\bar{x}_{Il}$
$l=1$	70.91	69.31	68.26	69.43	69.31	69.17	69.61	68.79	69.72
$l=2$	69.34	69.31	69.20	69.38	69.27	69.28	69.39	69.34	69.33
$l=3$	67.65	69.28	70.43	69.09	69.32	69.44	68.89	69.76	68.85
$\bar{x}_k$	69.30	69.30	69.30	69.30	69.30	69.30	69.30	69.30	69.30
D_k	1610.71	13.73	1135.09	129.94	20.17	142.86	312.26	463.20	425.28

Note: Average profit values are presented in the unit of RM ’000/hour.

Global mean $\bar{x}^m$ of Case 9 (from Table 4.10) = 69298 RM/hour

$\sum_{k=1}^{K} \max(\bar{x}_{kl}^m) - \bar{x}_k^m$ = sum of D_k for all cases = 4253 RM/hour

ANOM Optimum Profit Case 9 = 69298 + 4253 = **73551 RM/hour**

In this work, small deviation values of less than 1% for all Cases 1-9 are obtained. The results of profits comparison are presented in **Table 4.26**. This indicates that the optimum configurations of controllable factors for all the Cases 1-9 are successfully found. In addition, optimal configurations of noise factors can also be deduced from the global means of profit in all Cases 1-9. Based on the 243 experiments conducted previously, configuration J_3 K_1 in Run21_Case 7 yields a maximum profit of 123154 RM/hour. Combined with the configuration of noise factors J_3 K_1 from the previous results, the optimal configuration of both controllable and noise factors are A_1 B_1 C_3 D_1 E_3 F_3 G_1 H_3 I_1 J_3 K_1, which yields the highest profit of 124247 RM/hour. The optimum profit value showed that 24.9% of increment can be achieved as compared to the profit obtained at the base case condition (**Table 4.27**). The improved profit verifies the optimality of the Taguchi optimal configuration of both controllable and noise factors.

Table 4-26: CFU Profits at Optimal Conditions.

Case	Optimum Profit from Validation Run in HYSYS (RM ’000/hour)	Optimum Profit from ANOM (Eq. (8)) (RM ’000/hour)	Deviation (%)
1	113.71	114.11	0.3491
2	90.58	90.98	0.4378
3	67.46	67.86	0.5870
4	119.00	119.40	0.3357
5	94.66	95.06	0.4217
6	70.32	70.72	0.5668
7	124.25	124.67	0.3366
8	98.69	99.11	0.4234
9	73.13	73.55	0.5705

Table 4-27: Profit Improvement as Compared to Base Case Study

	Production Mass Flow Rate (kg/hour)					Profit (RM/h)	Profit Improvement (%)
	LPG	**LHN**	**HVN**	**Kero**	**Diesel**		
Base Case	16835	162483	107639	25709	34801	93323	24.9
Opt. Config.	17533	173393	110390	28280	35256	124247	

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5 CONCLUSION AND RECOMMENDATION

5.1 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. The results showed that five controllable factors (*A, C, H, I* and *G*) handling the pressure, temperature and production flow rate top the ranked list with a total contribution of 98.2% whereas the contribution of the other four factors are found trivial. The maximum CFU profit can be acquired from an optimal configuration of both controllable and noise factors based on the response plot of the averaged profit and SNR analysis. Validation runs are performed in HYSYS using the optimal configuration and the outputs are compared against those from ANOM. Remarkable agreements with an average deviation of 0.45% are found in all Cases 1-9 and the improved profit of 24.9% further verifies the optimality of configuration. The outcome from this work imply that Taguchi method can be employed in other processes due to its robustness in handling noise factors with the minimum number of experiments.

5.2 Recommendation

In the present work, case studies are generated based on the business scenarios (noise factors *J* and *K*). Both the noise factors are proven to be valid in influencing the objective function and their significances can be studied through the case studies generated using the Taguchi orthogonal array design.

Hence, for the future work, selection of noise factors can be based on the plant operation constraints such as column's tray efficiency, plant utility and energy usage, probability of equipment breakdown and etc. The case study conducted based on the combination of noise factors from the business and operation constraint scenarios will further improve the accuracy and reliability of the research work.

Complex scientific and statistical background are not required in Taguchi method, instead engineering solution is preferred. This approach is more understandable for practical engineers and it gives good results in practice. Hence, it is undeniably that Taguchi method will have a great potential application in the highly competitive and dynamic oil and gas industry due to its excellence performance in handling the noise factors and minimum amount of experiment which helps saving up time and resources.

CHAPTER 6

REFERENCES

6 REFERENCES

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