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Research Article

Analytic Hierarchy Process, Sensitivity Analysis, and Selectivity of Alphabutol Operation in 1-Butene Production

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In this study, different operating parameters which contributed to the fouling formation were identified, while taking into consideration the heat and mass and balance. The effects of three operational parameters viz: reactor temperature, reactor pressure, andcatalyst ratio, feed to and out of reactor and heat exchanger cleaning time on the optimal yield were succinctly investigated using an empirical mathematical model. The optimum per pass conversion (PPC) that maximizes yield and extends pump around loop (PAL) days in service was obtained using the analytic hierarchy process (AHP). The result obtained under the optimum operational condition shows an increased yield from 84 to 85.5% and a 1% improvement in the 1-butene selectivity. Moreover, due to the decrease in maintenance activities, production increased by 1000 tons per annum. In addition to this, the cleaning cycle of the pump around the loop was extended by 9 days and the man-hour cleaning requirement was reduced by 91 days. The operating time of the pump around the loop increased by 30 days per loop with a corresponding reduction in the cleaning time of 50 h which resulted in maximum yield. This study, therefore, presented a design from the sensitivity analysis conducted with the potential benefit of informed decision-making in the process of making a trade-off between optimizing variable cost with the cost of maintaining the Alphabutol technology.

1. Introduction

The growing need for 1-butene and plastic wrapping for a variety of food products, medicines, and other sectors upsurges demand for plastic materials and hence the 1-butene markets [1]. In the polyethylene processing industry, 1-butene is the most often deployed solvent. It is used in a range of polyethylene uses as a comonomer, comprising elastic and solid product packaging [2]. Due to its low volatility, low odor, and anaerobic biodegradability, it is an excellent material and sorter for a variety of industrial and commercial applications [3]. Asia-Pacific is the biggest market for 1-butene, and the region's fast expansion is driving demand in the polyethylene sector [4]. The increasing plastics industry in Asia-Pacific developing countries is driving demand for 1-butene in the nation [5]. Annually, both supply and demand for polyethylene grow, with 1-butene growing at an unparalleled pace [6]. Despite the present epidemic and its economic consequences, it has been predicted that demand would certainly grow in the following few years. Bland [5] reported on the worldwide consumption and demand for 1-butene and polyethylene. The annual growth rate was estimated to be 5.90 per cent, second only to propylene, which grew at a rate of 22.70 per cent from 2000 to 2017. Additionally, the projected annual growth rate for 1-butene was estimated to be 2.70 per cent from 2017 to 2022 and 6.20 per cent for propylene [1]. The technology of Alphabutol is used to produce polymerization grade 1-butene from high purity ethylene as the raw feedstock [7]. 1-butene is a comonomer utilized in the manufacture of various grades of polyethylene.

The Alphabutol technique, which works in the liquid phase and employs a dissolved catalyst, selectively dimerizes ethylene to form 1-butene. However, there are inherent drawbacks in the existing Alphabutol technological operations for the running of the units at a high production rate or optimizing the unit cost of production [7]. Making trade-offs between these two dilemmas has been a point of concern to many industries. It is important to know that many industries are confronted with the problems of running the pump around a loop (PAL) due to an unimaginable drop in the overall heat transfer coefficient (U) occasioned by fouling in the pipes [8]. To therefore mitigate these effects, the risk of performing trials on an industrial scale is reasonably risky due to the high residence time involved and the inability to control the chain reaction involved [8]. It is therefore necessary to study the effects of reactions parameters on a commercial plant scale [2]. The effects of operating parameters such as catalyst ratio, pressure, temperature, per pass conversion (PPC) on the yield, selectivity and side-polymers formation are therefore essential. The analytic hierarchy process (AHP) technique is a tried-and-true approach and one of the best—known decision-making strategies used by many industries. One benefit of this strategy is its ability to analyze the relative priority levels of variables or alternatives and indicate the optimal option [9]. There are three aspects to the AHP approach of problem-solving. The first portion deals with the problem at hand, while the second part explores the many options for resolving it. The third and most critical aspect of the AHP technique is the criteria utilize to assess the alternative solutions. The calculations made by AHP can often be influenced by the expertise of decision-makers, which means that the AHP should be regarded as an instrument that can convert the assessments made by the decision-maker into a multi-criterion ranking (qualitative and quantitative). Furthermore, the AHP is straightforward so the decision-maker has no need to construct a sophisticated expert method [10]. In contrast, the AHP can require a number of user feedbacks, especially in case of problems with various requirements and choices. Each assessment is very straightforward, however, because only the decision-maker has to articulate the comparison of two alternatives and parameters. The burden of the assessment task could be unfair. The number of comparisons combined with the number of parameters and alternatives actually increases quadratically [10]. In addition, the sensitivity analysis is a critical step in deciding whether the solution is stable and implementable when constructing models using the analytic hierarchy process. The main aim of this research is to develop an integrated solution with APH to determine the best-operating conditions for the Alphabutol technology which can maximize yield, selectivity, and pump around loop days in service and minimize pump around loop cleaning time, coupled with sensitivity analysis of variable cost as a trade-off of maintenance cost for the different region in the globe. The main objective is to study how those input characteristics affect the output response per pass conversion (PPC) and its effect on the outputs parameters such as yield, selectivity, and pump around loop days in service and cleaning hours.

2. Materials and Methods

In this study, data were collected using different operating parameters, after which an empirical mathematical modeling was developed. The AHP was used with experts to decide on the importance of each variable which was thereafter preceded by sensitivity analysis. First, all equipment used, including the transmitter, digital weighing scales, and gas chromatograph, was calibrated at the beginning of the experiment. This indicated that all the models of the equipment used in the experimental work will be sufficient. Equipment leaks were prevented with the aid of a vacuum sealer and an eye on the sample take-off and conditioning panel. An exclusive uniform titanium-based catalyst was used in the Alphabutol® pilot plant, which shows significant dimerization efficiency and outstanding selectivity to 1-butene at low pressures and temperatures (Figure 1). This efficiency is measured by the catalyst content and reaction settings. On the other hand, ethylene polymer is produced as a by-product of the catalytic dimerization of ethylene to 1-butene. In this procedure, there are three stages: reaction, catalyst clean-up, and distillation. The reactor operates in the liquid phase at bubble point conditions in the reaction portion. As part of the process, the gas distributor feeds ethylene into the liquid phase, which contains butene and hexene [2].

2.1. Design of Experiment. For the design of the experiment, a complete factorial 2K model was used with ‘K’ representing the input variables [11]. The process starts with selecting the parameters to be used in the analysis such as but not limited to reactor pressure, reactor temperature, catalyst flow, and ratio. These variables were varied and the effect on the output such as PPC, yield, selectivity, days in service, and cleaning time was monitored. The factors’ levels were set to high and low values, which confined the experimental range by providing information solely within the variable’s setting (identifying factors). The experimental runs were detailed once the variables and their associated set levels were selected. The variables used in each experiment were different [12]. A three-factor factorial experiment with eight experimental runs was used in this study. Initially, it was expected that the variables influencing the output response would have a linear relationship. In general, this is a reasonable initial guess. The inclusion of a central point with more than two levels of data allowed researchers to see whether the connection had any curvature to it [13]. Lower and upper limits for optimum parameters were determined using preliminary data collected for more than 300 days, with a particular emphasis on mass and heat balance in a wide variety of operating conditions across the plant. The upper and lower limits of each variable were chosen because of the runaway or slow reactions that might occur beyond higher and lower levels, respectively. Table 1 summarizes the selected experimental variables and their values, as well as the experiment design, which consists of eight separate runs and a central point.

The derived generalized equations containing the three identifying factor as above is presented in equation (1):

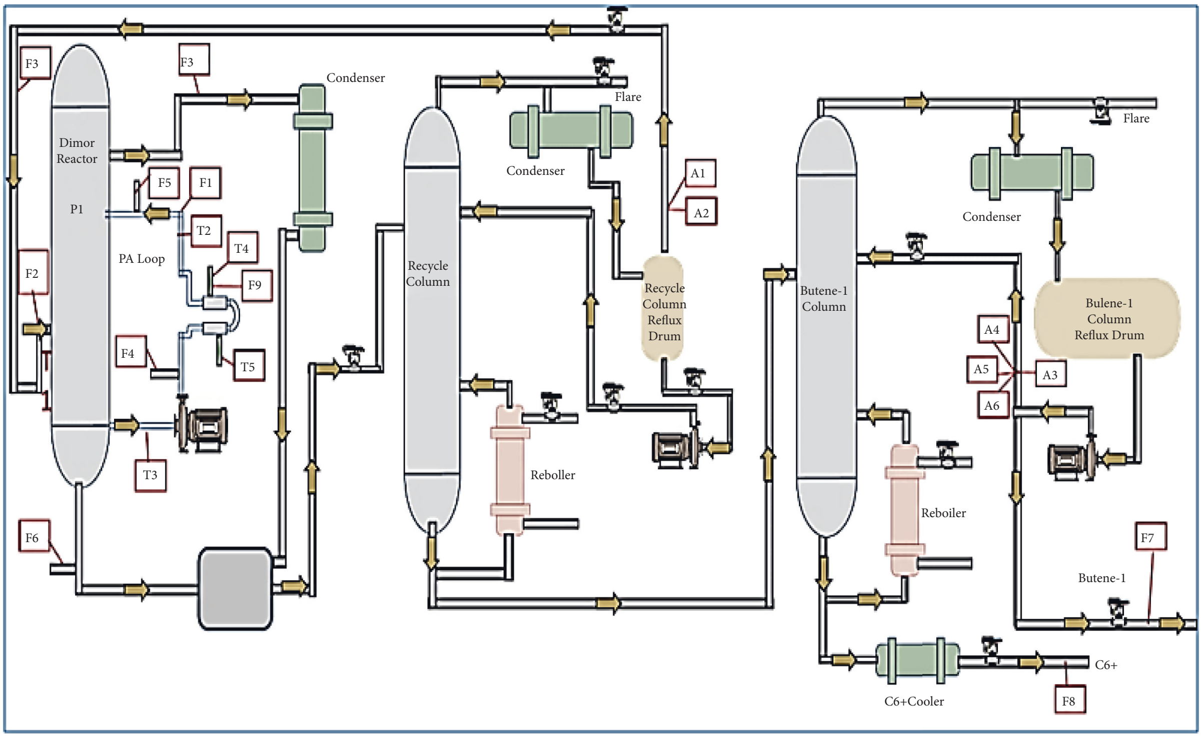

Figure 1: Alphabutol® Schematic process flow diagram.

Table 1: Identifying factors, low and high setting of the three factors.

Variables	Symbols	Low setting (−1)	High setting (+1)
Reactor temperature (°C)	X_1	48	54
Reactor pressure (kg/cm^2g)	X_2	18	21
T2/LC mole ratio	X_3	1.8	2.5

$$\begin{aligned}\text{Log}\,(PPC) &= 2.036078 - 0.011213 * X_2 \\ &\quad + 0.00195 * X_1 + 0.012571 * X_3,\end{aligned} \qquad (1)$$

where X_2 is pressure in kg/cm^2 or kPa, X_1 is temperature in °C, and X_3 is mole catalyst ratio.

The primary purpose was to determine the effect of those input features on the output response associated with each pass conversion (PPC). This is the main equation used in calculating the PPC and it is obtained from the Design of Experiment (DoE) using JMP statistical software as shown in Tables 2 and 3 and Figure 1. Per pass conversion (PPC) and then what is the per pass conversion (PPC) and how does it affect the following plant outputs: yield, selectivity, pump around the loop, days in service, and cleaning hours. The pass per conversion (PPC%), yield, and selectivity were estimated from the mass balance of the plant as presented in the following equation:

$$\text{PPC} = 1 - \left(\frac{(((100 - A_1 - A_3)/100) * t\,(F_{10} + F_3))}{(\,(((100 - A_1 - A_3)/100) * (F_{10} + F_3)) + F_2)} \right) * 100, \qquad (2)$$

where A_1 is ethane recycled in PPM, A_3 is 2-butene in the 1-butene product in PPM, F_2 is ethylene feed flow in kg/h, F_3 is recycled ethylene flow in kg/h, and F_{10} is purge flow in kg/h.

$$\text{Yield\%} = \frac{F7}{F2}, \qquad (3)$$

where F_2 is ethylene feed flow in kg/h and F_7 is 1-butene production flow in kg/h.

$$\text{Selectivity\%} = \frac{F7 * (A6/100)}{(F7 * (A6/100)) + F8}, \qquad (4)$$

where A_6 is 1-butene purity in the 1-butene product in ppm, F_7 is 1-butene production flow in kg/h, and F_8 is C_{6+} production flow in kg/h.

As shown in Table 4 of the experimental run schedule, a complete factorial DoE with three factors produces eight trials in addition to one full center point. Since this is a commercial-scale plant experiment, a (−) is often used for temperature 50 and a (+) for temperature >52, a (−) is mostly used for pressure 19 and a (+) is often used for pressure >20, and a (−) is more often used for catalyst ratio 1.9 and a (+) is most often used for ratio >2.2. Each element was given a value between 1 and 1, as shown in Table 4. For instance, the nominal value of the reactor temperature of 50°C is denoted by "−1," whereas any temperature more than 52°C is denoted by "+1." The other two variables were treated similarly [14]. The purpose of assigning −1 and +1 values is to establish a constant scale across all variables. The schedules for each run

Table 2: Summary of data collection.

Run	X_1 (°C)	X_2 (kg/cm^{2}g)	X_3	PPC (%)	Yield (%)	Selectivity (%)	PAL in service days (S)	PAL cleaning hours (h)
1	53.86	21.28	2.30	85.6%	87.27%	89.86%	28	312
2	50.70	20.66	2.16	86.5%	87.26%	92.51%	41	292
3	52.69	19.03	2.31	90.3%	85.22%	87.72%	29	280
4	51.19	20.38	2.12	87.1%	82.26%	90.01%	40	288
5	49.90	20.16	2.14	86.9%	83.56%	90.02%	33	252
6	51.40	21.19	2.51	83.2%	82.89%	88.44%	21	223
7	51.24	18.85	2.00	89.4%	82.13%	88.75%	31	336
8	49.96	19.38	1.98	88.2%	85.51%	89.21%	43	384
9	52.37	21.12	2.21	85.8%	88.58%	91.75%	54	350

are shown in Table 4. The center points (C) are 51°C in temperature, 20 kg/cm2 in pressure, and a TEAL/LC ratio.

2.2. Analytic Hierarchy Process (AHP). The analytic hierarchy process (AHP) is often used to determine the parameter's level of relevance in operating the unit using AHP's basic scale of pairwise comparison for the optimal PPC per cent value to run to maximize yield, selectivity, pump around loop days in service, and minimal cleaning time [15]. Pairwise comparisons are conducted using the basic scale of pairwise comparisons with grades ranging from 1 to 9. A simple, but extremely plausible, assumption: If attribute A is more significant than attribute B and has a rating of 9, then B must be less important than A and has a rating of 1/9. All factors, often no more than seven, are compared pairwise, and the matrix is finalized. Hence, the analytic hierarchy process (AHP) is a mathematical decision-making approach that takes qualitative and quantitative factors into account while making judgments. It simplifies complicated judgments by comparing them one-on-one (pairwise) and then synthesizing the findings. In contrast to other strategies such as ranking or rating, the AHP makes advantage of the human capacity for comparing individual qualities of alternatives. It not only assists decision-makers in selecting the best option but also gives a concise justification for the selection. Thomas Saaty developed the procedure [16]. A group of Subject Matter Experts (SME) determined the parameter's level of relevance in operating the unit using AHP's basic scale of pairwise comparison. To rank the priorities, equation (5) was used:

$$\lambda_{\max} = A * X, \tag{5}$$

where A is the comparison matrix of size $n \times n$, for n criteria, X is the eigenvector of size $n \times 1$, and $\lambda_{\max}$ is the eigenvalue. If $\lambda_{\max} < n$; then successive squared powers of the matrix are followed by normalizing the row sums until the difference between successive row sums is less than a prespecified value (approximately zero) in the iteration process [17]. The next stage is the calculation of the consistency ratio (CR) to measure how consistent the judgments have been relative to large samples of purely random judgments. CR is calculated as a random consistency divided by consistency index (CI). The CI is calculated using equation (6), in which the upper row is the order of the random matrix, and the bottom row is the corresponding index of consistency for random judgments.

$$\text{ConsistencyIndex}\,(\text{CI}) = \frac{\lambda\max - n}{n-1}. \tag{6}$$

If the CR is more than 0.1, the judgments are unreliable because they are too near to randomness, rendering the exercise worthless or requiring repetition.

2.3. Sensitivity Analysis of Unit Parameters and Cost. The sensitivity analysis was conducted in this study to examine the effect of changing operational parameters on variable costs, such as the catalyst ratio, which affects fouling and cleaning cycle frequency. These studies will weigh the man-hours required for maintenance and the unit's prolonged life against the variable cost of output (especially catalyst cost). Using a global benchmark for maintenance salaries based on official reports [18], as well as chemical prices based on the licensor's quote and contract. The comparison in this study will be made based on variable costs and maintenance costs since maintenance costs vary according to wage levels in various parts of the globe. The experiment was conducted on this plant since it is capable of being commercialized. The method was to be carried out at a constant temperature of 53°C and at the constant pressure of 21 kg/cm^2 (2059 kPa), with the only variation being the mole ratio of catalyst, which ranges between 1.5 and 3.0. These mole ratio fluctuations were recorded for the same pump across the loop to monitor its activity as well as the reaction conditions. Seven runs were achieved over a year. The purpose of this procedure was to determine how long a pump around a loop could operate before being completely fouled, and subsequently how long it required cleaning. The cost of the catalyst is determined using the following equation:

$$C = P * \left(\left(L_c * \frac{T_m}{R * 5.5}\right) + \left(T_c * T_m\right)\right), \tag{7}$$

where C is the catalyst cost in \$, P is plant capacity in tons usually 20 KTA, L_c is titanium catalyst (type-2253) unit cost in \$; T_m is Teal material factor; R is desired catalyst mole ratio; T_c is Teal unit cost in \$, and 5.5 is the conversion from weight ratio to mole ratio. Moreover, the maintenance man-hour cost is calculated as per equation (8):

$$\text{MC} = \left\{\left(\frac{365}{S}\right) * H * P * N * Mn\right\}, \tag{8}$$

Table 3: Estimation of the expected model's parameters using JMP.

Term	Estimate	Std error	T ratio	Prob > ItI	* VIF
Intercept	2.036	0.011	185.01	<0.0001	
Reactor Pressure	−0.01121	0.00027	−40.86	<0.0001	1.095
Reactor Temperature	0.0019503	0.00023	8.25	0.0004	1.295
Teal/LC, Mole Ratio	0.01257	0.002746	4.58	0.0060	1.248

*VIF = Variance inflation factor

where MC is the man-hours cost in \$; 365 is the number of days in a year, H is cleaning hours; S is pump around loop days in service; P is the number of the pump around loop s usually 3; N is the number of the crew usually 5, and M_n is the man-hour wage in \$.

3. Results

3.1. The Influence of Reaction Parameters on the Results. The summary of the results from the trials of the experiment is shown in Table 2, along with the average of all data for each run. Over 300 data points were collected during the trial. This occurred because the facility was operational at all times save for power outages or scheduled shutdowns. In all, 300 data points were evaluated using JMP software to create a mathematical model of PPC and its relationship to the key factors. To examine descriptive statistics, the JMP program began with a running histogram of all key variables. The run revealed the major factors' influence on PPC. The JMP program was used. JMP software is utilized in this work to conduct experimental runs for mathematical modeling of PPC. The major variables given in Table 2 are gathered throughout nine experiment runs involving three distinct loops. The anticipated equation is PPC = f (P, T, R) which denoted that PPC is a function of P, T, and R. The 300 data points were selected to represent nine tests inside the permissible operating windows for each parameter, from lowest to the maximum value, encompassing center points [14].

The observations are as shown in Figure 1 as an outcome of the data collection and analysis in the JMP programmed as a leveraged plot with the variable on the X-axis and the PPC on the Y-axis. The blue line represents the variable's average value, whereas the red line represents the line of best fit. The red area around it denotes the border of the fit's 95 per cent confidence interval. If the blue line is in the red zone, suggesting multi-collinearity, or if the VIF (variance inflation factors) is large, all the individual leverage plots do not display the butterfly pattern and are therefore acceptable as an independent variable, as shown in Figure 2. If the JMP graphs exhibit a visual butterfly effect, this indicates that the variance inflation factors (VIF) are more than 5, indicating that the variables are reliant on one another.

However, there is no butterfly effect in the data, i.e., VIF less than 5. As a result, the variables are unrelated to one another [18, 19]. VIF was about 1.2 for this model, as given in Table 3, which is less than 5, and in conjunction with Figure 1, which indicates no visual butterflies, the model is confirmed. The temperature, pressure, and teal/catalyst mole ratio of the reactor are all major independent factors that determine the PPC per cent. The VIF values and model parameter estimates for the best fit are shown in Table 4; this table was derived from JMP [14]. From the generalized model in equation (1), containing three identifying factors, the model parameters are generated as given in Table 4.

The predicted mathematical equation of PPC obtained from JMP as per Table 4 shows the intercept and parameter estimate as logarithmic; hence PPC equation is shown as equation (1). In this equation, R^2 measures the proportion of total variability in the response model [20]. The R^2 for this model was obtained as 99%. From equation (1), pressure has a negative impact on PPC, which means that higher pressure results in lower PPC. The temperature and catalyst ratio, however, have a positive impact on PPC. Thus, a higher temperature and catalyst ratio results in higher PPC. This model meets all conditions, which are: the model residuals should follow a normal distribution, the average value of the residuals should be zero, the residuals should be random and should not be heteroscedastic, i.e., should not exhibit a pattern, and residuals should not be auto-correlated (Figure 3). In addition, this model has high R^2 of 99% and no lack of fit [21].

According to the individual graphs in Figure 1, the PPC per cent rises with decreasing pressure and decreases with increasing reactor temperature, and the teal/catalyst mole ratio is as follows: increased reactor pressure decreases PPC, polymer formation, C6+, and 1-butene synthesis, since increased pressure assures that the catalyst is more active owing to enhanced monomer diffusion; hence, good selectivity [22]. The reaction loop's ethylene concentration is easily monitored by pressure control when the reactor is operating at its bubble point [23]. As pressure is a critical parameter in the reactor, an advanced process control (APC) is necessary to regulate it, and the employment of a dynamic model in a predictive multivariable controller enables this to be implemented. By regulating the catalyst flow with APC, it is feasible to limit the disturbances that impact the pressure gradient from the reaction mixture to the active dimerization [24]. A decrease of 1 kg/cm^{2}g may boost PPC by 2.2 per cent at constant temperature and catalyst ratios. A rise in the reactor temperature results in an increase in PPC, polymer formation, C6+ generation, and a reduction in 1-butene selectivity. These are the hypotheses explored for the process in which a continuously stirred tank reactor (CSTR) is utilized. In a CSTR, one or more fluid reagents are supplied into a tank reactor and stirred continuously while the reactor effluent is withdrawn; perfect mixing is also necessary when residence time is taken into account. Additionally, dimerization is an exothermic process, which means that its kinetics increase with temperature and might result in a

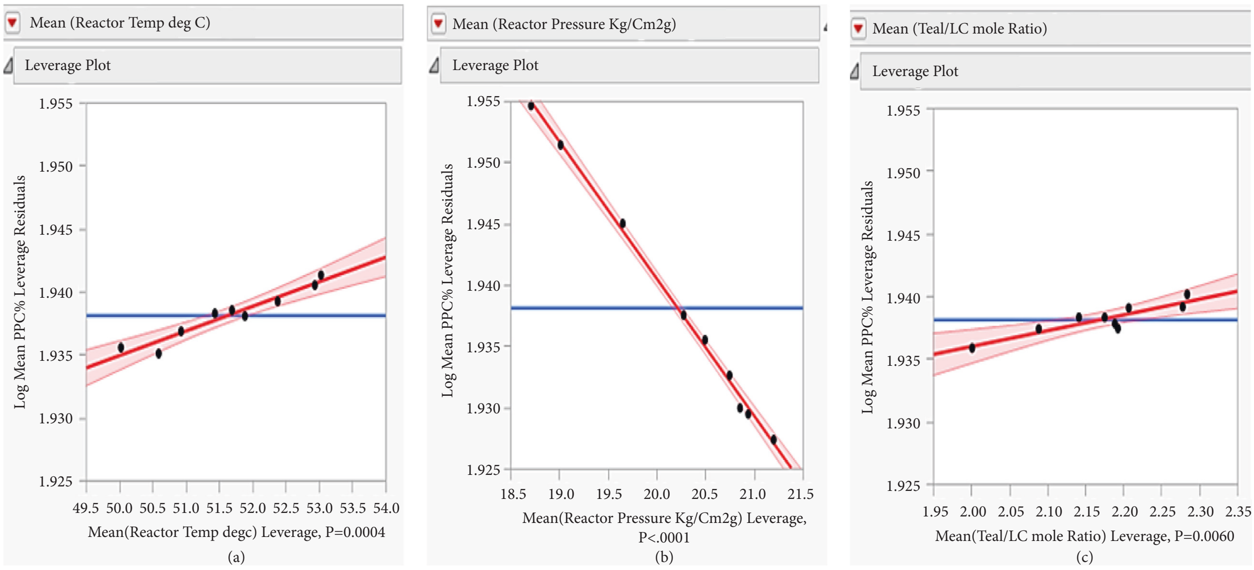

FIGURE 2: Leverage plot for the three variables (a) Temperature (b) pressure, and (c) catalyst ratio.

TABLE 4: Experimental trial matrix.

Run	X_1 (°C)	X_2 (kg/cm^{2}g)	X_3
Experiment 1	+	+	+
Experiment 2	C	+	C
Experiment 3	+	−	+
Experiment 4	C	C	C
Experiment 5	−	+	−
Experiment 6	C	+	+
Experiment 7	C	−	−
Experiment 8	−	−	−
Experiment 9	+	+	C

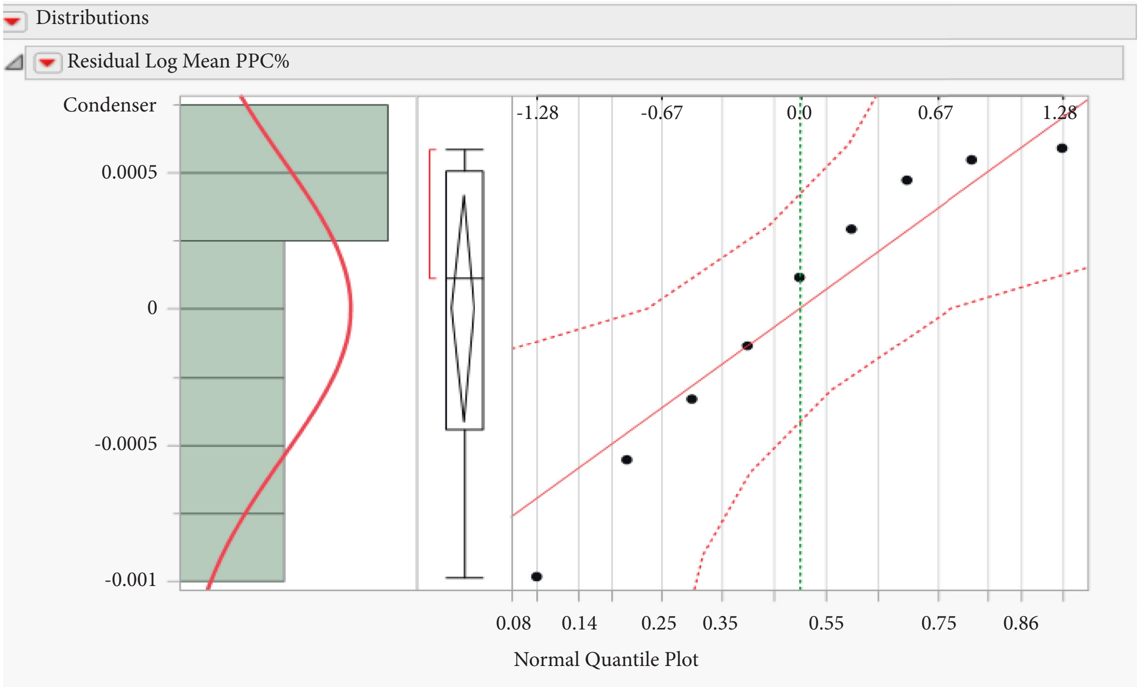

FIGURE 3: Model residual analysis quantile plot.

Table 5: Pairwise Comparison.

	Yield	Run days	Cleaning time	Run consistency	Selectivity
Yield	1	3	5	5	1
Run days	0.33	1	3	2	2
Cleaning time	0.20	0.33	1	1	1
Run consistency	0.2	0.50	1	1	1
Selectivity	1	0.50	1	1	1
Sum	2.73	5.33	11	10	6

Table 6: Normalized matrix.

	Yield	Run days	Cleaning time	Run consistency	Selectivity	Weight
Yield	0.366	0.563	0.455	0.500	0.167	40.991
Run days	0.122	0.188	0.273	0.200	0.333	22.310
Cleaning time	0.073	0.063	0.091	0.100	0.167	9.865
Run consistency	0.073	0.094	0.091	0.100	0.167	10.490
Selectivity	0.366	0.094	0.091	0.100	0.167	16.344

Table 7: Random consistency value.

Matrix size	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.89	1.12	1.25	1.32	1.41	1.45	1.49

runaway reaction [25]. A temperature rise of 1°C increases PPC by 0.4 per cent at constant pressure and catalyst ratio. Increased catalyst ratio results in an increase in PPC, polymer formation, C6+ reduction, and 1-butene synthesis. Even at the optimal ratio, a small amount of polymer is generated as a side reaction; nevertheless, when the ratio exceeds 3, the balance of ethylene is tipped toward the formation of high molecular weight polyethylene, as acknowledged by several research findings that conclusively proved that ethylene dimerizes selectively to 1-butene at low ratios, so even though higher ratios result in a significant loss of dimerization center activity due to the presence of free AlEt3 coming. At constant pressure and temperature, increasing the catalyst ratio by 0.1 resulted in a 0.25 percent increase in PPC.

3.2. *The Selection of Optimum PPC using AHP.*

The analytic hierarchy process (AHP) was used to estimate the optimal PPC per cent value to run to maximize yield, selectivity, pump around loop days in service, and minimal cleaning time. Table 5 illustrates the parameter's pairwise comparisons. The SME team received together to discuss the relative relevance of the various parameters and how they interacted with one another.

The numbers in Table 5 are based on importance as determined by a team of subject matter experts who have worked in this plant for many years, using the AHP method. This means that yield is 3 times more important than a run day, 5 times more important than cleaning time, 5 times more important than consistency, and as important than selectivity. These ratings were done in a brainstorming and alignment session of all SMEs in the plant running this unit. Then, the matrix of Table 5 is squared to get the weight.

The weight of each factor was calculated by dividing the importance intensity scale by the sum of each factor and normalizing the matrix, as shown in Table 6. The results shown in each field are the result of dividing the importance of each parameter in Table 5 over the sums appeared in the same table. For example, yield of 0.366 is the result of dividing 1 over 2.73 equal to 0.366, and so on.

Table 7 shows the random consistency (RC) matrix as determined by the AHP method for the five variables in the matrix. The value of RC is 1.12 as shown in Table 7 since the matrix size is 5.

Then, the matrix of Table 5 is squared to get the weight. The normalized weight is called eigenvector as shown in Table 8. Squaring the matrix was done by normal matrix multiplication, for example, the yield value in Table 8 comes from Table 5 as follows: summation of the first row multiply by the first column. Thus, $(1 * 1 + 322170.33+ \quad 5 * .20 + 5 * 0.2 + 1 * 1) = 5.$ Or by using Microsoft excel workbook as: "INDEX (MMULT)". The normalized eigenvector in Table 8 is obtained as row sum for the parameter divided by total sum. For example, yield is $\{80.6/(80.6 + 40.33 + 17.51 + 30.90)\}$ which is 0.43 and so on for all parameters. The difference column is the difference between the current normalized eigenvector minus previous iteration Eigenvector. The final Eigenvalue or λ is obtained by the sum of normalized Eigenvector multiply by its importance. Finally, $\lambda_{\max}$ was obtained by λ divided by the normalized Eigenvector. The SME can select what value of PPC is the best to give the optimum condition. The sum of the index in each column is calculated by giving a (+) for yield, selectivity, Run days, and (−) for cleaning hours and consistency. The rank is obtained by selecting the higher index as given in Table 9.

Table 8: Squaring pairwise comparison table.

	Yield	Run days	Cleaning time	Run Consistency	Selectivity	Row Sum	Normalized Eigen Vector	Difference	final Eigenvalue λ	$\lambda_{\max}$
Yield	5.00	10.67	25.00	22.00	18.00	80.67	0.43	0.06	2.20	5.14
Run days	3.67	5.00	11.67	10.67	9.33	40.33	0.21	0.09	1.16	5.44
Cleaning time	1.71	2.27	5.00	4.67	3.87	17.51	0.09	0.02	0.51	5.53
Run Consistency	1.77	2.43	5.50	5.00	4.20	18.90	0.10	0.03	0.55	5.48
Selectivity	2.57	4.83	9.50	9.00	5.00	30.90	0.16	−0.20	0.89	5.44

Table 9: Final AHP decision table and ranking.

Experiment #		1	2	3	4	5	6	7	8	9
Yield	0.41	36.16	36.16	35.31	34.08	34.63	34.35	34.03	35.43	36.70
Run days	0.22	6.16	9.03	6.38	8.80	7.26	4.62	6.82	9.47	11.89
Cleaning time	0.10	30.24	28.30	27.14	27.91	22.29	21.61	32.56	37.21	33.92
Run Consistency	0.10	0.003	0.006	0.004	0.005	0.003	0.005	0.005	0.003	0.005
Selectivity	0.16	14.82	15.26	14.47	14.85	14.85	14.59	14.64	14.71	15.13
Index		26.91	32.14	29.02	29.82	34.45	31.94	22.93	22.39	29.80
Rank		7	2	6	4	1	3	8	9	5
PPC	Mean	85.6%	86.4%	90.1%	87.2%	86.8%	82.7%	89.4%	88.1%	85.7%

From Table 9, the best PPC to be run all the time is 86.8% or 87%. This means that at 87% PPC, the plant will have the maximum run days and less cleaning time with higher selectivity and yield. This conclusion came as a result of the AHP decision table with the index and rank calculation. These results were tested again in the plant to choose the best temperature T, pressure P, and catalyst ratio R. The plant now is controlled at 87% PPC by controlling P, T, and R since the PPC equation was used to calculate T, P, and ratio as per optimization. However, if the plant management wanted to run at a certain PPC% then using equation From equation (1) and choosing the desired temperature and catalyst ratio with variable pressure as in Table 10 which gives PPC% for the fixed temperature of and catalyst ratio of, the only variable is pressure.

Table 10: PPC% at different pressures with constant temperature and catalyst ratio.

PPC%	Temperature (°C)	Catalyst ratio	Pressure (Kg/cm^2)
86	51	2.3	20.56
87	51	2.3	20.11
88	51	2.3	19.64
89	51	2.3	19.19

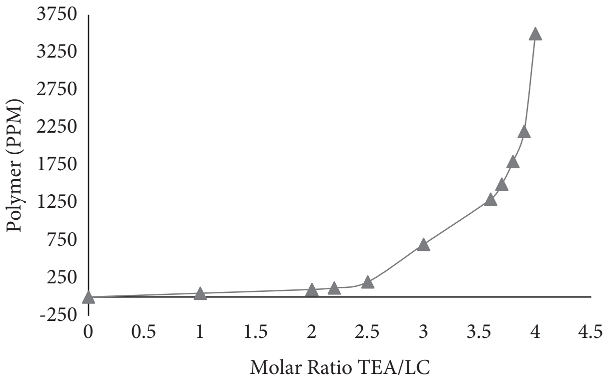

Figure 4: Relationship between catalyst ratio and polymer.

3.3. Sensitivity Analysis. It is critical to optimize the cost between variable and fixed costs. The cost of labor and chemicals are factors in this optimization. There is a link between the catalyst ratio and the quantity of polymer formed as a side reaction from dimerization of ethylene utilizing LC and TEAL catalysts in this study. Figure 4 depicts the link between polymer generated in ppm and molar ratio of the catalyst according to the technology pilot plan lab. The observed results reveal a rapid rise in polymer production when the molar ratio TEAL/LC increases. These demonstrate a direct relationship between polymer production and molar ratio. As the molar ratio grows, so does the possibility of fouling effects in the system, which in turn raises the cost of PAL maintenance.

Figure 5 represents a separate experiment that displays the cleaning time contrasted with different catalyst ratio values at constant reactor temperature and pressure. According to the data acquired from the investigation between molar ratio and cleaning hours, the greater the molar ratio, the quicker it fouls and the longer it takes to clean. As shown in Figure 3, the catalyst ratio is proportional to the number of polymers, which implies that more polymers need more cleaning. A lower ratio will therefore require a shorter cleaning time. The cleaning time spent cleaning a pump around a loop was recorded, and so choosing the proper ratio is critical economically to the site with varied pay conditions in different modes. 1-butene

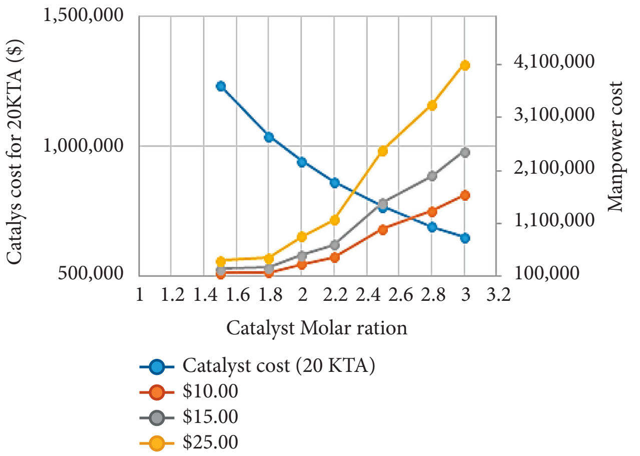

Figure 5: Comparison between catalyst cost and manpower cost at different wages.

production requires a 2.5 molar ratio catalyst and 8 and 40 kg of TEAL/LC-2253, respectively, costing $8 and $40 per kg. Figure 3 compares alternative molar ratios and labor costs for a 20,000-ton nominal 1-butene manufacturing unit per year. Cleaning time and catalyst cost may be optimized by enterprises in various countries with varied salaries. For a 20,000-ton-per-year factory, the catalyst cost is an easy estimate to do because of the material factor for each raw material and catalyst. Five maintenance experts are needed to clean the three-pump-around-loop system once a year. Hydro blasting devices are often used to clean heat exchangers by those specialists. It will cost $ 944,000 to produce 20 KTA of 1-butene at a mole ratio of 2.0.

Similarly, with the same catalyst ratio of 2.0, the maintenance costs are estimated at 340,000 dollars per man-hour at a 10 dollar cost. This indicated that a location or area may choose the optimization that best meets their needs, such as running the ratio at 2.4 all the time since the catalyst cost is lower per year than the labor cost if maintenance rates are $15 per hour. If the cost of labor per hour is $25, the lower the cost-to-income ratio, the better. Keep in mind that from an operational and safety standpoint, it's best to keep the plant running at all times, since downtime might result in an Environment, Health and Safety (EHS) crisis. As a result, operating petrochemical plants is safer than shutdown and starting up.

4. Conclusion

This study has successfully developed an integrated solution to determine the best-operating conditions for the Alphabutol system which can minimize the pump around the loop (PAL) fouling, coupled with sensitivity analysis of variable cost as a trade-off of maintenance cost. The result shows that the pressure has a negative impact on PPC which means the higher the pressure, the lower the PPC. The temperature and catalyst ratio, however, have a positive impact on PPC thus the higher the temperature gives higher PPC; similar to the catalyst ratio effect. It was recommended to run PPC at 87% where the temperature is fixed as 51°C with a catalyst ratio of 2.3. The only variable was the pressure at the desired PPC which will be 20.11 kg/cm^2. Once the pressure and temperature are fixed, the only way to increase (or decrease) the feed input will be by changing the flow of the catalyst. An increased catalyst flow means a higher conversion of ethylene, hence a lowering trend of the pressure which will be balanced by the opening of the ethylene feed valve through the action of the reactor pressure control. Following inferences were made on the performance of the Alphabutol operation; the yield experienced an improvement from 84% to 85.5% with an improved selectivity of 1-butene by 1%. The production increased by 1000 tons per year as a result of less maintenance in cleaning and hence the cost reduction. Also, the pump around the loop (PAL) cleaning cycle was extended from 21 days to 30 days, indicating a 9 day extra production time. The man-hours for cleaning of side-product became reduced from 387 hours to 296 hours. Furthermore, from the sensitivity analysis conducted, this research, therefore, provided a roadmap in the process of reaching a balance between optimizing variable costs or continuing with the cost of maintenance of the Alphabutol technology. From the result of the study, it is recommended that the stakeholders make an informed decision in optimizing the process rather than continuing with the bogus cost of maintenance. This will in no doubt increase the production time and reduce the depreciation of the equipment. However, it is up to the plant site to decide which value suits them. [26].

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

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