International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 1, Januaryr- 2013

Application Of Analytic Hierarchy Process (AHP) In The Selection Of An Effective Refinery For Life Cycle Cost Analysis.

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Abstract

Rising cost of ownership in today's competitive oil refining industry has created the need for an effective refinery that can successfully meet the refiner's overall operational demand. A life cycle cost analysis that considers system effectiveness of oil refineries will be a promising tool that can enhance total life cycle cost reduction. It is, therefore, important that decisions on cost are not made in isolation of effectiveness of the system. The purpose of this paper is to select an effective topping refinery among several alternatives using the Analytic Hierarchy Process (AHP). The selected option could be further evaluated to determine its life cycle cost. A panel of experts, made up of refinery operators and designers was put together to develop the system effectiveness criteria, and to select the topping refinery options to be used in the AHP analysis. The AHP hierarchy developed in this study is a three level process in which the top level represents the main goal of effective refinery selection and the lowest level comprises the alternative topping refineries. The criteria that influence the primary goal are included at the second level and are related to different system effectiveness requirements. Finally, based on the selected system effectiveness criteria, the topping refineries are ranked using the pairwise comparisons matrix of AHP to determine the most effective scheme. The presented AHP hierarchical structure represents a well balanced synthesis of various system effectiveness factors that must be taken into consideration when making complex decision of this nature.

Keywords: System effectiveness; Analytic hierarchy process; Topping refinery; Life cycle cost.

1. Introduction

In the oil refining industry, global competition and rising cost of ownership have created the need to consider system effectiveness in the life cycle cost analyses of oil refineries (Okafor, 2011). The main objective is to ensure that decisions on cost are not made in isolation of effectiveness of the system. The incorporation of system effectiveness in the life cycle cost analyses of oil refineries is bound to influence the design change of the plant and provides explanation of the relationship between cost and design parameters that could enhance total life cycle cost reduction.

Researcher and authors (Kawauchi and Rausand, 1999; Vorarat and Al-Hajj, 2004; Singh and Tiong, 2005; Iwawaki *et al*, 2002) have emphasized the need for a life cycle costing framework that will not only consider total cost but also system effectiveness. Engineering analyses attract attention because systems fail, and they seldom fail on schedule (Emblemsvag 2003). Consequently, life cycle cost analysis that ignores system effectiveness will omit relevant costs and risks, and thus present results that are out of touch with reality. Life cycle cost being the incorporation of all costs associated with a system, from conception to disposal (Waghmode et al, 2010) is, therefore, closely connected to the effectiveness and efficiency of a system. This assertion is true for open complex systems like the oil refineries that have long life cycles.

System effectiveness relates to the capability of a system to fulfil a defined requirement (Fabrycky and Blanchard, 1991). It is a function of some effectiveness attributes associated with the design of oil refinery, e.g. reliability, maintainability, capacity, and flexibility. However, some of these attributes are quite intangible in nature and even the tangible ones can only be modelled from past historical data of similar plants working under similar conditions. Unfortunately, these data are not always readily available. As a result, the evaluation of options for system effectiveness was carried out using the Analytic Hierarchy Process (AHP) to select the most effective topping refinery from three alternatives. The selected alternative could be further evaluated to ascertain its life cycle cost. It is important to emphasize that though, the developed novel life cycle costing (LCC) framework can predict the life cycle costs of oil refineries considering plant effectiveness, the evaluation of system effectiveness shall be separated from the evaluation of cost. However, the purpose of this paper is to demonstrate the application of AHP in the selection of an effective topping refinery.

The AHP technique uses expert opinion and judgment in complex decision making scenario. This technique developed by Thomas Saaty (Saaty, 1980) is a robust and flexible multi – criteria decision making (MCDM) technique for complex problems where both qualitative and quantitative aspects are considered. The choice of AHP amongst other multi- criteria decision making techniques is because it provides a convenient way to quantify the qualitative attributes of the options presented, hence removing subjectivity in the result (Tiwari, 2006). Its matrix of pairwise comparisons can be utilized to subjectively establish the relative weight between criteria, and alternatives. Though, AHP is based on subjective judgments from expects, it has an indispensable characteristic that other subjective methods lack, i.e. an integral logical consistency check (Emblemsvag, 2003).

This research was conducted and concluded in November, 2011 at Cranfield University, United Kingdom.

2. Theoretical framework

The main thrust of this paper is based on the theory of AHP. The paper describes the use of AHP in the selection of the most effective topping refinery. AHP takes into consideration the decision makers' personal inconsistencies as their judgments as human beings with respect to qualitative issues are seldom consistent. The AHP accommodates and quantifies these inconsistencies in the analysis. An inconsistency ratio of less than 0.1 (10 percent) shows that the result is sufficiently accurate but if greater than 0.10, the result may be less predictable and may require re-evaluation. Lee and Kim (2001) opined that decision makers feel comfortable with AHP because it is simple and easy to understand.

The AHP assists the analyst to organize the essential aspects of a problem into a hierarchical pattern. Moreover, by reducing complex decisions to a series of simple comparisons and rankings, and later synthesizing the results, the AHP not only assists the analyst to arrive at the best decision but provides clarity in the manner the choices are made (Bevilacqua and Braglia, 2000). The AHP has particular application in group decision making (brainstorming).

The overall procedure of the AHP is as follows:

a. Definition of decision criteria in the form of a hierarchy of objectives. The hierarchy is structured at different levels from the top (the goal) through intermediate levels (criteria) to the lowest level (the alternatives).
b. The criteria are weighted as a function of their importance for the corresponding element of the higher level. For this purpose, AHP uses simple pairwise comparisons to determine weights and ratings so that the analyst can concentrate on just two elements at a time.
c. After the development of a judgment matrix, a priority vector to weight the elements of the matrix is calculated.

Saaty (1986), Harker and Vargas (1987) state the axioms of AHP as follows:

i. Homogeneity: This axiom states that comparisons are meaningful if elements are comparable. Hence, we cannot compare refineries with flowstations.
ii. Dependence: This axiom allows comparisons among a set of elements with respect to another element at the higher level. Consequently, comparisons at the lower level depend on the element at the higher level.
iii. Expectations: This axiom simply states that any change in the structure of the hierarchy will require new evaluations of preferences for the new hierarchy.
iv. Reciprocal condition axiom: This axiom is derived from the intuitive idea that if an alternative or criterion ‘A’ is n times preferred to ‘B’, then ‘B’ is 1/n times as preferred as ‘A’.
v. Inconsistency ratio: An inconsistency ratio (IR) of 0.10 (i.e. 10 percent) or less is a positive evidence of an informed judgment.

3. Methodology

The AHP hierarchy developed in this study is a three level process in which the top level represents the main goal of effective refinery selection and the lowest level comprises the alternative topping refineries. The criteria that influence the primary goal are included at the second level and are related to different system effectiveness requirements. The development of the system effectiveness criteria and the selection of topping refinery options were carried out by a panel of experts (decision makers) in consonance with the author.

A panel of experts (decision makers) was put together to encourage communication and meetings where expert opinions and knowledge could contribute to the process. The panel was made up of three (3) PhD researchers in the School of Engineering, Cranfield University, whose research studies are mainly focused on oil refinery scheduling, operations, planning, and design parameters.

The chairperson of the three-man panel of experts is a chemical engineer with a total of 17years experience in petrochemical process plant design in Nigeria and UK. She has worked in various capacities as a trainee manager, assistant maintenance manager, and refinery operations manager. The second panellist is a petrochemical engineer with a total of 10years working experience in oil refinery scheduling and planning. He is the project manager of an oil and gas servicing company in Nigeria. His company in collaboration with its foreign technical partners handles the turnaround maintenance of some oil refineries in Nigeria. He has benefitted from various overseas training programmes in the past. The third panellist is a chemical engineer with 9years working experience as an independent consultant saddled with the responsibility of conducting training programmes on refinery operations and economics for oil servicing companies in Nigeria and South Africa.

The establishment of this panel proves to be appropriate for this type of study because it allows expert opinions and knowledge to be obtained on a subject matter. The panel (decision makers) worked for a period of two weeks, and each session lasted for two hours.

The search for criteria was first conducted by the panel (decision makers), where ten (10) system effectiveness criteria were identified, namely: availability, reliability, maintainability, flexibility, capacity, supportability, dependability, readiness, adaptability, and safety. To limit the complexity of the analysis to be undertaken, the number of evaluation criteria was reduced to four (4) by categorising similar attributes and discarding the less important ones. The four system effectiveness criteria chosen by the panel (decision makers) are reliability, maintainability, capacity, and flexibility. These criteria were selected because of their impact on refinery operation, maintenance, production, and adaptation. The panel argued that a plant which is reliable and maintainable leads to optimum availability and user satisfaction, while flexibility and capacity may have direct impact on the refiner's revenue (return on investment) and business sustainability. Furthermore, three alternatives of topping refinery (Preflash Drum Scheme, Prefractionator Scheme, and Dual Drum Scheme) were identified for the study.

Bevilacqua and Braglia (2000) state that "an increase in the number of parameters does not imply a higher degree of analysis accuracy". With a large number of attributes, the quantitative evaluation of the factors becomes more complex and subject to the risk of inaccurate results. Moreover, most of the above-mentioned system effectiveness criteria are not easy to evaluate because of their complex and intangible nature. Mean-time-between-failure (MTBF) and mean-time-to-repair (MTTR) which are random variables in reliability and maintainability respectively are some tangible aspects that can only be estimated from failure data in existing plants (oil refineries), working under similar conditions. But unfortunately these data may not be readily available (Gluch and Baumann, 2004). For the resolution of this problem, a multi-criteria decision making approach using the AHP was proposed, where both qualitative and quantitative aspects could be considered.

3.1 *Topping Refinery*

The first and foremost refinery configuration is the topping refinery which is designed to separate the crude oil into its constituent petroleum products by atmospheric distillation process (Speight, 2011). Topping refinery consists of tankage, an atmospheric tower, side strippers, desalter, crude furnace, heat exchangers, pumps, recovery facilities for gases and light hydrocarbons, and the necessary utility systems.

The topping refineries in Figures 1, 2, and 3 were chosen for this study because the topping refinery is the first and essential building block in any refinery complex. Moreover, it is the main unit upon which other units derive their complexities. Thus, refinery complexity indicates how complex a refinery is in relation to the topping refinery. The complexity index of refinery 'R' is determined by the complexity of each individual unit weighted by its percentage of topping refinery (Gary *et al*, 2007).

The three alternatives of topping refinery are:

a) *Preflash Drum Scheme*

The desalted crude oil is heated, and then introduced to a preflash drum where flashed water and light hydrocarbons are separated. The flashed vapour is sent directly to the atmospheric tower. The flashed liquid is further heated by heat exchangers and a crude oil furnace. This system reduces pressure drop through the crude oil furnace, and prevents mal-distribution of crude oil to the furnace tube passes.

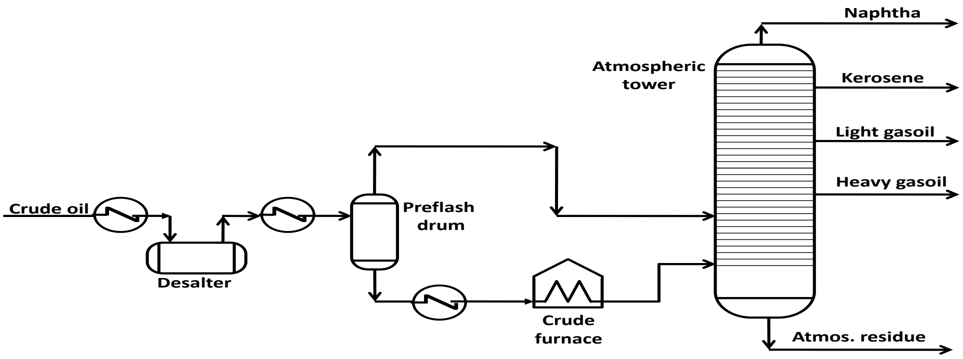

Figure 1. Preflash Drum Scheme (Hori, 2000)

b) *Prefractionator Scheme*

A prefractionator is installed to remove gas and part of naphtha from the crude oil. Since gas and part of the naphtha are removed in the prefractionator, the diameter of the atmospheric tower can be reduced. The pressure drop through the feed furnace may also be reduced. This system is often applied when processing crude oils that are rich in gas and naphtha fractions. It is also applied as a means of increasing the capacity of an existing unit.

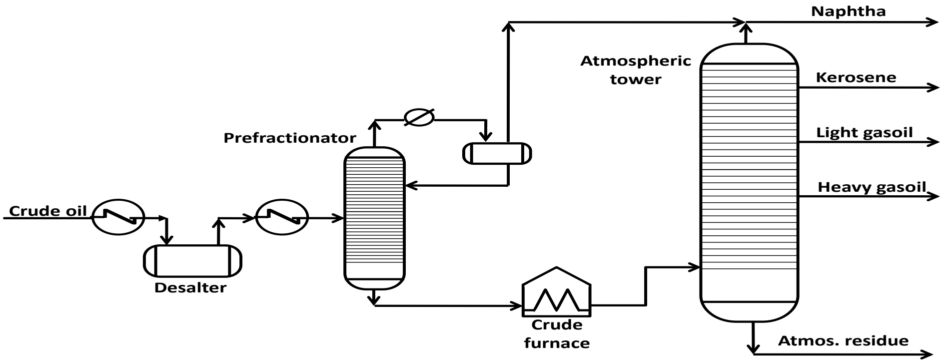

Figure 2. Prefractionator Scheme (Hori, 2000)

c) *Dual Drum Scheme*

This system is applied to process two or more kinds of crude oil whose properties, e.g. sulphur content are very different. An additional crude feed train provided with flash drum is installed to yield separately the residue from each crude oil.

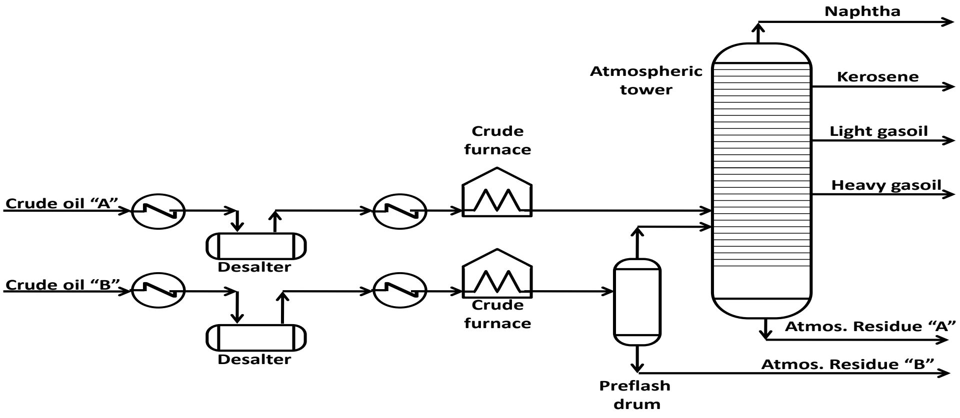

Figure 3. Dual Drum Scheme (Hori, 2000)

3.2 *System effectiveness*

Fabrycky and Blanchard (1991) defined system effectiveness as "the probability that a system or product can successfully meet an overall operational demand within a given time when operated under specified conditions". Thus, system effectiveness relating to the ability of a topping refinery to fulfil the user's overall operating requirement is a function of the following attributes: reliability, maintainability, capacity and flexibility. The above-mentioned attributes are useful to the decision makers in subjectively assessing the level to which each alternative satisfies the system effectiveness criteria.

a) *Flexibility*

Flexibility is the ability to adapt to changes in requirement. It can be achieved through the ability to expand the production facility and sharing of resources (Ishizaka and Labib, 2011). When a system user is confronted by evenly-matched options, a flexible solution that works for both options is attractive. Ellingham and Fawcett (2006) state that it is reasonably easy to estimate the cost of providing an option to switch use, but valuing the option is a bigger task.

b) *Reliability*

"Reliability is the probability that an item can perform a required function under given conditions for a given time interval" (Kawauchi and Rausand, 1999; Sheikh *et al*, 1990). Operational reliability plays an active role in the process of decision making. Reliability, which is expressed in terms of mean-time-between-failure (MTBF), is a major parameter in determining operation and maintenance costs in life cycle cost analysis.

c) *Capacity*

Charge capacity represents the input capacity of the refinery unit while production capacity represents the maximum amount of refined streams that can be produced. One of the factors that have a major effect on a refiner's profit is the charge and production capacities of a plant. Topping, hydroskimming, cracking and coking refineries are described in terms of their charge capacity, which describes the input feed capacity of the plant. Refineries generally have an on-stream (full capacity) factor of about 92% to 96% (Gary *et al*, 2007).

d) *Maintainability*

"Maintainability is the probability that an item will be retained in or restored to a specified condition within a given period of time when maintenance is performed in accordance with prescribed procedures and resources" (Fabrycky and Blanchard, 1991). It therefore measures the ease and speed with which a system can be restored to operational condition after a failure. Maintainability is a design parameter which impacts on life cycle cost, especially operation and maintenance costs. In maintainability, the random variable is mean-time-to-repair (MTTR).

4. Results and Discussion

The AHP hierarchy for this decision is shown below:

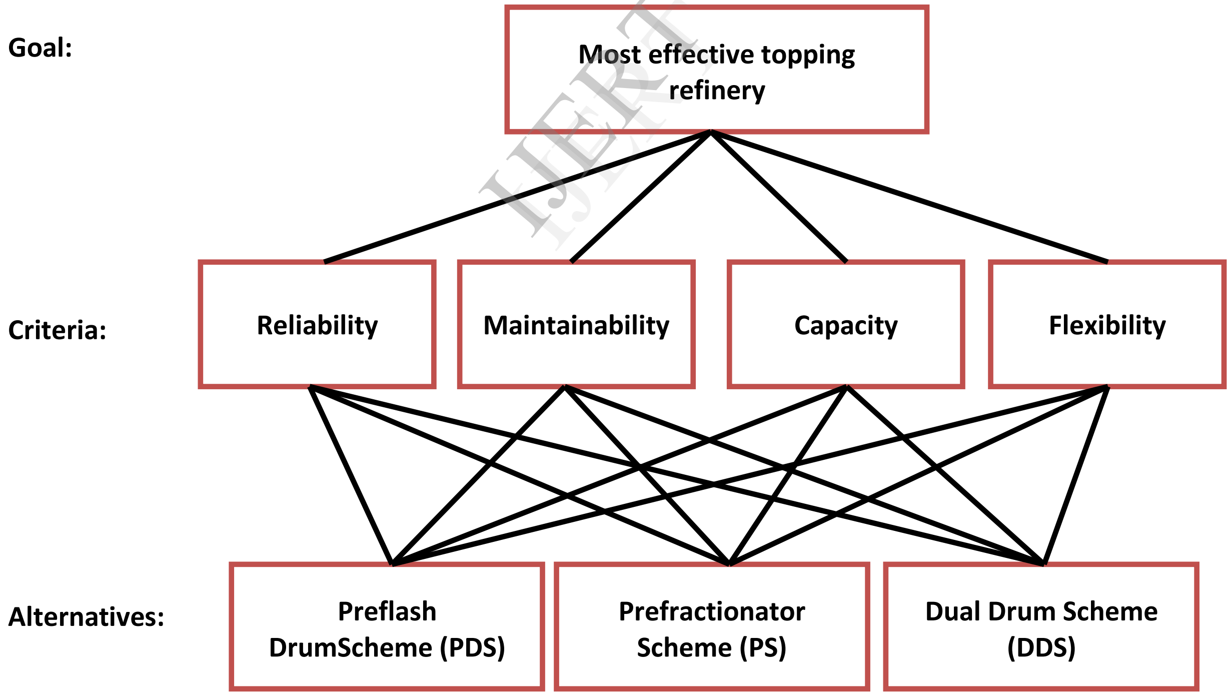

Figure 4. Decision hierarchy for the selection of an effective refinery

4.1 Pairwise Comparison

As the AHP analysis progresses, the priorities for the alternatives will be determined with respect to each of the decision criteria, and priorities for each of the criteria with respect to their importance in reaching the goal.

The priorities will be derived from a series of measurements: pairwise comparisons involving all the elements. The elements at each level will be compared, two by two, with respect to their contribution to the element above them. The comparisons will begin by comparing the alternatives with respect to their strengths in meeting each of the criteria. The next step will be to compare the criteria with respect to their importance to reaching the goal. Since we have three alternatives and we need to compare each one to each of the others, we will make three pairwise comparisons with respect to each criterion: PS vs. DDS, PS vs. PDS, and DDS vs. PDS. Preflash Drum Scheme is 'PDS', Prefractionator Scheme is 'PS', and Dual Drum Scheme is 'DDS'.

The AHP Fundamental Scale in assigning the weights is stated below in Table 1.

Table 1. The Fundamental Scale for Pairwise Comparisons (Saaty, 1980)

Intensity of Importance	Definition (Judgement)	Explanation
1	Equal Importance	Two elements contribute equally to the upper level criteria.
3	Moderate importance	Experience and judgement moderately favour one element over another.
5	Strong importance	Experience and judgement strongly favour one element over another.
7	Very strong importance	One element is favoured very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation.

Note: Intensities of 2, 4, 6, and 8 can be used to express intermediate values.

4.2 Alternative versus Criteria

The next step will be to compare pairs of alternatives with respect to Reliability. The Decision Makers will decide for each comparison which alternative is the weaker with respect to Reliability, giving its reliability a weight of 1. Using the AHP Fundamental Scale (Table 1), the Decision Makers will assign a weight to the reliability of the other alternative. The comparisons are summarized below in Table 2.

Table 2. Alternatives compared with respect to RELIABILITY

PS	1	DDS	3	DDS reliability is moderately preferred to that of PS. Weight: 3
PS	3	PDS	1	PS reliability is moderately preferred to that of PDS. Weight: 3
DDS	5	PDS	1	DDS reliability is strongly preferred to that of PDS. Weight: 5

Key: PDS is Preflash Drum Scheme, PS is Prefractionator Scheme, and DDS is Dual Drum Scheme.

The next step is to transfer the weights to a matrix, using a method unique to the AHP.

Reliability	PS	DDS	PDS	Priority
PS	1	1/3	3	0.258
DDS	3	1	5	0.637
PDS	1/3	1/5	1	0.105

Sum of Priorities 1.00
Inconsistency 0.04

By processing this matrix mathematically, the AHP derives priorities for the alternatives with respect to reliability. Priorities are measurements of their relative strengths, derived from the judgment of the decision makers as entered into the matrix. These can be calculated by hand, or with a spreadsheet programme, or by using specialized AHP software (Expert Choice 11).
They are shown above to the right of the matrix, along with an Inconsistency Factor (Saaty, 2006). ***However, in this study, Expert Choice 11 (AHP software) was used to compute the priorities and inconsistency ratios.***

Table 3. Alternatives compared with respect to MAINTAINABILITY

PS	3	DDS	1	PS maintainability is moderately preferred to that of DDS. Weight: 3
PS	1	PDS	4	PDS maintainability is more than moderately preferred to that of PS. Weight: 4
DDS	1	PDS	5	PDS maintainability is strongly preferred to that of DDS. Weight: 5

Key: PDS is Preflash Drum Scheme, PS is Prefractionator Scheme, and DDS is Dual Drum Scheme.

The next step is to transfer the weights to a matrix, using a method unique to the AHP.

Maintainability	PS	DDS	PDS	Priority
PS	1	3	¼	0.226
DDS	1/3	1	1/5	0.101
PDS	4	5	1	0.674

Sum of Priorities 1.00
Inconsistency 0.08

Table 4. Alternatives compared with respect to CAPACITY

PS	1	DDS	5	DDS capacity is strongly preferred to PS capacity. Weight: 5
PS	3	PDS	1	PS capacity is moderately preferred to PDS capacity. Weight: 3
DDS	7	PDS	1	DDS capacity is very strongly preferred to PDS capacity. Weight: 7

Key: PDS is Preflash Drum Scheme, PS is Prefractionator Scheme, and DDS is Dual Drum Scheme.

The next step is to transfer the weights to a matrix, using a method unique to the AHP.

Capacity	PS	DDS	PDS	Priority
PS	1	1/5	3	0.188
DDS	5	1	7	0.731
PDS	1/3	1/7	1	0.081

Sum of Priorities 1.00
Inconsistency 0.06

Table 5. Alternatives compared with respect to FLEXIBILITY

PS	1	DDS	4	DDS flexibility is more than moderately preferred to that of PS. Weight: 4
PS	3	PDS	1	PS flexibility is moderately preferred to that of PDS. Weight: 3
DDS	7	PDS	1	DDS flexibility is very strongly preferred to that of PDS. Weight: 7

Key: PDS is Preflash Drum Scheme, PS is Prefractionator Scheme, and DDS is Dual Drum Scheme.

The next step is to transfer the weights to a matrix, using a method unique to the AHP.

Flexibility	PS	DDS	PDS	Priority
PS	1	¼	3	0.211
DDS	4	1	7	0.705
PDS	1/3	1/7	1	0.084

Sum of Priorities 1.00
Inconsistency 0.03

4.3 Criteria versus the Goal

As the decision makers have evaluated the alternatives with respect to their strength in meeting the criteria, they will now evaluate the criteria with respect to their importance in reaching the goal. In this case, the decision makers have agreed on the following relative weights for the various pairs of Criteria.

Table 6. CRITERIA compared with respect to reaching the GOAL

Reliability	2	Maintainability	1	Reliability is somewhat moderately more important than Maintainability. Weight: 2.
Reliability	4	Capacity	1	Reliability is somewhat strongly more important than capacity. Weight: 4.
Reliability	5	Flexibility	1	Reliability is strongly more important than flexibility. Weight: 5.
Maintainability	2	Capacity	1	Maintainability is somewhat moderately more important than Capacity. Weight: 2.
Maintainability	3	Flexibility	1	Maintainability is moderately more important than Flexibility. Weight: 3
Flexibility	1	Capacity	2	Capacity is therefore, somewhat moderately more important than Flexibility. Weight: 2.

Pairwise comparison of four elements requires six separate comparisons, while that of three elements require three.

The number of comparisons can be calculated using the following formula: $\frac{n(n-1)}{2}$

Where n is the number of elements. The above-mentioned pairwise comparisons of the four elements require a larger matrix.

Table 7. Priorities of all Criteria in reaching the Goal

Criteria	**Reliability**	**Maintainability**	**Capacity**	**Flexibility**	**Priority**
Reliability	1	2	4	5	0.507
Maintainability	1/2	1	2	3	0.264
Capacity	1/4	1/2	1	2	0.143
Flexibility	1/5	1/3	1/2	1	0.086

Sum of Priorities 1.00
Inconsistency 0.01

From this decision, Reliability, the highest ranked Criterion in reaching the Goal, is about twice as important in reaching the goal as the second highest ranked Criterion, Maintainability. Similarly, Maintainability is about twice as important as Capacity, which in turn is about twice as important as Flexibility.

4.4 Final Priorities Synthesis

As we have known the priorities of the Criteria with respect to the Goal, and the priorities of the Alternatives with respect to the Criteria, we can conveniently calculate the priorities of the Alternatives with respect to the Goal.

Table 8. Calculations for the Alternatives with respect to the Criteria

Priority (Criterion versus Goal)		Alternative	X		Y		Z
Reliability	0.51	Prefractionator Scheme	0.258	x	0.51	=	0.13
		Dual Drum Scheme	0.637	x	0.51	=	0.32
		Preflash Drum Scheme	0.105	x	0.51	=	0.05
			1.00				0.51
Maintainability	0.26	Prefractionator Scheme	0.226	x	0.26	=	0.06
		Dual Drum Scheme	0.101	x	0.26	=	0.03
		Preflash Drum Scheme	0.674	x	0.26	=	0.18
			1.00				0.26
Capacity	0.14	Prefractionator Scheme	0.188	x	0.14	=	0.03
		Dual Drum Scheme	0.731	x	0.14	=	0.10
		Preflash Drum Scheme	0.081	x	0.14	=	0.01
			1.00				0.14
Flexibility	0.09	Prefractionator Scheme	0.211	x	0.09	=	0.02
		Dual Drum Scheme	0.705	x	0.09	=	0.06
		Preflash Drum Scheme	0.084	x	0.09	=	0.01
			1.00				0.09

Key: Column X shows the priorities of the alternatives with respect to the Criteria.
Column Y shows the priority of the criteria with respect to the goal.
Column Z shows the product of the two, which is the global priority of each alternative with respect to the goal.

Table 9. Overall priorities for all the Alternatives

Alternative	Global Priority with Respect to				
	Reliability	Maintainability	Capacity	Flexibility	Goal
PS	0.13	0.06	0.03	0.02	0.24
DDS	0.32	0.03	0.10	0.06	0.51
PDS	0.05	0.18	0.01	0.01	0.25
Total:	0.51	0.26	0.14	0.09	1.00

Key: PDS is Preflash Drum Scheme, PS is Prefractionator Scheme, and DDS is Dual Drum scheme.

4.5 Discussion

Consequent upon the AHP result, the Dual Drum Scheme that can process two or more kinds of crude oil has the highest overall priority of 0.51 in reaching the goal. The Preflash Drum Scheme with overall priority of 0.25 is second while the Prefractionator Scheme at 0.24 overall priority is third. However, results from Table 9 (overall priorities for all the alternatives) show that the Prelash Drum Scheme has the highest priority of 0.18 in terms of maintainability. The Dual Drum Scheme has thehighest priorities of 0.32, 0.10, and 0.06 in terms of reliability, capacity, and flexibility respectively to emerge the most effective topping refinery.

5. Conclusion

There has been an unprecedented interest in recent times in the assessment of the system effectiveness of new and existing refineries due to the rising cost of ownership. The proposed AHP approach will serve as a useful tool for decision makers to appraise the range of performance issues that need to be considered when making complex decisions concerning system effectiveness of oil refineries. Moreover, the AHP hierarchical structure in this paper presents a well balanced synthesis of various system effectiveness factors that must be appraised by managers for a plant to be more competitive.

Despite the limited number of experts which has challenged the validity of the AHP result, the proposed approach can be easily applied to other industrial plants when there is dearth of historical performance data. Future publication will be extended to describe a novel AHP-LCC framework that seeks total life cycle cost reduction of oil refineries.

Acknowledgement

The author wishes to thank the Nigerian Tertiary Education Trust Fund (TETFund) for funding this research.

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