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## Articles

**Covenant Journal of Engineering Technology (CJET) Vol. 2, No. 2, Dec.. 2018**

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# Performance Indicators for Sustainable Cement Production in Nigeria

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***Abstract***: The cement industry is an intensive energy consuming process with attendant economic benefits and environmental caution. Cement processing comes with economic advantages and environmental implications, like dust and pollutants. Host communities and staff of cement factories are bound to experience and endure this barrage of emissions, which leads to serious health and environmental challenges. Using the Analytic Hierarchy Process (AHP), three cement manufacturing companies in Ogun State, South-West, Nigeria were investigated to determine how best they conform to industry best practices. Fifteen criteria were identified and used for this analysis. Results show that COMPANY B is operating at acceptable standards while COMPANY A should consider improving on safety, spares, emission levels and staff welfare.

***Keywords***: Sustainable, Cement, AHP, Best Practices, Pollution

## I. Introduction

Cement manufacturing is an intensive energy consuming process considered to be one of the world's most highly energy intensive economic sectors. Cement manufacturing comes with economic advantages and environmental implications, which poses grave serious health and environmental implications on people and the environment. These include emissions of airborne pollution in the form of dust, gases, noise and vibration when operating machinery and during blasting in quarries, and damage as a result of quarrying operation. The typical gaseous emissions to air from cement manufacturing plants include Nitrogen Oxide (NOx), Sulphur dioxide (SO2), Carbon monoxides (CO), Carbon dioxides (CO2) and dust. Added to this, the industry has also been regarded as an intensive consumer of natural raw materials, fossil fuels, energy, labour [1-4]. According to the Cement Sustainability Initiative [5], fatalities are the most serious tragedy that can happen in the Cement Industry. It is of essence to derive the best possible fatality prevention strategy. Analysis by region indicated much higher risk in developing regions such as Asia, Africa and South America.

The study aims to carry out performance evaluation for selected cement plants in Ogun state Nigeria, to investigate how they keep to the industry's best practices and compare results to one another. The analysis of this study will be done using the Analytic Hierarchy Process AHP). One of the most useful methods for selecting, ranking and investigation that is becoming more and more important is the Analytic Hierarchy Process (AHP). This method was developed by Saaty as a tool to help with solving technical and managerial problems. The Analytic Hierarchy Process (AHP) can also be defined a multi-criteria decision making method that helps the decision-maker facing a complex problem with multiple and subjective criteria in making decisions. The main objective of the AHP is to identify the preferred alternative and also determine a ranking of the alternatives when all the decision criteria are considered at the same time [6-8].

Fifteen criteria were identified for a proper performance evaluation of the selected cement plants - production capacity, safety, ease of production setup, topography, availability, spares, down times, capital cost, energy cost, maintenance cost, staff welfare, emission levels, noise level, cost of raw materials and dust level. This study is limited to Ogun State in South-West, Nigeria and can be expanded in the near future. The three cement plants investigated are COMPANY A, COMPANY B and COMPANY C and are located in Ogun State, South-West Nigeria. These cement plants are also referred to as alternatives in this paper.

## II. Materials and Methods

*Identifying relevant criteria*

The study adopted the identification of relevant criteria that will bridge the gaps between product quality, quantity, sustainable manufacturing, energy consumption, pollutant emissions and safety in the cement industry. Upon review of literatures and assessing performance indicators, fifteen relevant criteria were chosen.

*Conducting Industry Survey*

Data was sourced using questionnaire method. The questionnaires were completed by engineers who are staff of the case study companies. They work in the production, logistics, safety and quality control departments. Twenty properly completed questionnaires were selected for each company and used for this study. In order to define a unique value for the judgments of these engineers based on our questionnaire, the arithmetic mean of each question scale was calculated.

*Analytic Hierarchy Process*

An AHP-based evaluation model can be developed for investigating the degree of adherence of cement plants to best practices to ensure proper safety, health and energy standards by following the steps below [9]:

- Step 1: Define the evaluative criteria for investigating the degree of adherence of cement factories to best practices to ensure proper safety, health and energy standards.
- Step 2: Establish a hierarchical structure. Acquire important indicators into a hierarchy of interrelated decision elements, including goal, criteria and sub-criteria where necessary. The established hierarchy tree is shown in Figure 1


Figure 1: Problem hierarchy tree

- Step 3: Establish the pair-wise comparison matrix. Each decision maker makes a pair-wise comparison of the alternatives with respect to a criterion and assigns them relative scores.

For this analysis,

- Let n be the size of the square matrix, i represents a row index of an element of A and j represents a column index of an element of A, then:
- Let the pairwise comparison matrix be A, then the elements of A can be identified by indices, i and j. Therefore: A=Aij. The numeric values assigned to each element is based on Saaty’s Rating Scale as shown in Table 1.

Table 1: Saaty's Rating Scale

| Value | Description of comparison |
|---|---|
| 1 | Two elements contribute equally to the objective |
| 3 | Experience and judgment slightly favour one element over another |
| 5 | Experience and judgment strongly favour one element over another |
| 7 | An element is favoured very strongly over another; its dominance demonstrated in practice |
| 9 | The evidence favouring one activity over another is of the highest possible order of affirmation |
| 2,4,6,8 | Intermediate values |

- Step 4: Determine the eigenvalue and eigenvector of each pair-wise comparison matrix. Given that AHP analysis is defined by the expression:

  $A \times \omega = \lambda_{max} \cdot \omega$

  Where **ω** is an eigenvector and $\boldsymbol{\lambda_{max}}$ is the mean eigenvalue.

$$N_j = \sqrt[n]{\prod_{j=1}^{j=n} A_{ij}}$$

$$N = \sum_{j=1}^{n} N_j$$

$$\omega_j = N_j / N \qquad \{j=1, 2, 3\ldots n-1, n\}$$

$\omega_j$ is an element of **ω** which is a column vector and:

$$\sum_{j=1}^{n} \omega_j = 1$$

- Step 5: Test the consistency of each comparison matrix, using the following expression:

  $$CI = \frac{(\lambda_{max} - n)}{(n - 1)}$$

- Step 6: Select the appropriate Random Index. The Random index (RI) is useful in order to determine how good the Consistency Index (CI) is. AHP compares CI to [RI] and this comparison result in what is termed as Consistency Ratio. Random Index is the Consistency Index of a randomly generated reciprocal matrix from the scale 1 to 9 [11]. A sample of RI values for matrix of the order 1 to 15 can be found in the Appendix section.
- Step 7: Calculate the consistency ratio. Consistency ratio can simply be defined using the expression below:

  $$\mathbf{CR} = \frac{CI}{RI}$$

For a set of judgment, the consistency index estimated is divided by the random index corresponding to the order of the matrix. The resulting value is termed as the consistency ratio. The value determined is very useful in indicating consistency of judgments made during pairwise comparison. The difference, if any, between $\boldsymbol{\lambda}_{\mathbf{max}}$ and **n** is an indication of the inconsistency of the judgments. If $\boldsymbol{\lambda}_{\mathbf{max}}$ = **n** then the judgments have turned out to be perfectly consistent. Perfect consistency rarely occurs in practice. In the AHP the pairwise comparisons in a judgment matrix are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% [12].

- Step 8: Steps 3 to 7 are repeated for all criteria. The column vector **ω** is derived for each criteria considered. The derived column vectors are assembled into an 'eigenvector matrix'.
- Step 9: Pairwise comparison is also done for all criteria by comparing them with each other. Steps 3-7 are also repeated to determine consistency. The elements of derived eigenvector in this step are the 'criteria weights'. Criteria weight show priorities or importance of the criteria considered by experts or decision makers.

  The criteria weights arrived at in this paper were based on the judgment of experts and are presented in the appendix section.
- Step 10: Calculate the overall composite weight to rank the alternatives. The alternatives are ranked from the most suitable to the least based on the magnitude of their corresponding overall composite weight.

Eigenvector matrix **x** Criteria weights = Overall Composite Weight [13]

## III. Results

The criteria weights of all the criteria are presented graphically in Figure 2. It can be deduced that safety and the cost of raw materials are of the highest priority while topography is of the least priority.

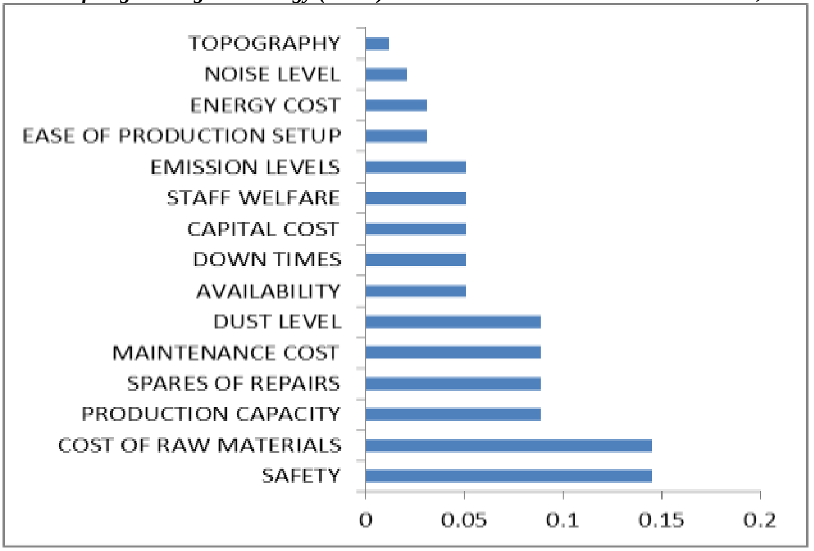


Figure 2: Graphical presentation of criteria weights

***Using Ease of Production Setup Criteria for Comparison***

Based on the criterion, Figure 3 depicts that COMPANY B cement plant has the highest value while COMPANY A has the least.

***Using Production Capacity Criteria for Comparison***

By relative weights, COMPANY B cement plant has the highest relative weight and COMPANY A has the smallest, as shown in Figure 4.

***Using Safety Criteria for Comparison***

Figure 5 illustrates that COMPANY C cement plant has the highest relative weight and COMPANY A has the smallest.

***Using Topography Criteria for Comparison***

Figure 6 graphically presents COMPANY B cement plant having the highest relative weight, while COMPANY A has the smallest.

***Using Availability Criteria for Comparison***

COMPANY B cement plant has the highest relative weight and COMPANY A has the smallest. This is presented in Figure 7.

***Using Spares Criteria for Comparison***

Figure 8 illustrates that COMPANY B cement plant has the highest relative weight and COMPANY A has the smallest.

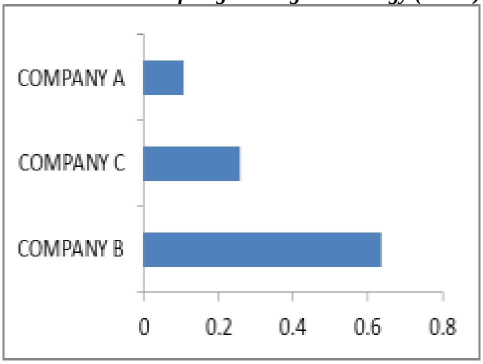


Figure 2: Relative weights for Ease of production setup

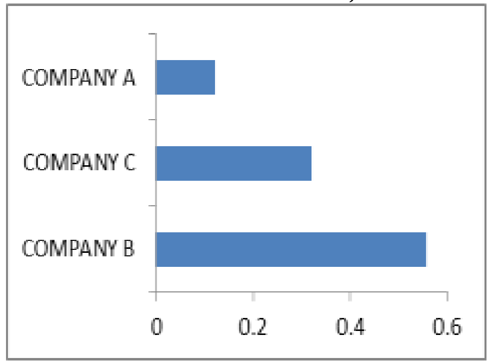


Figure 3: Relative weights for production capacity

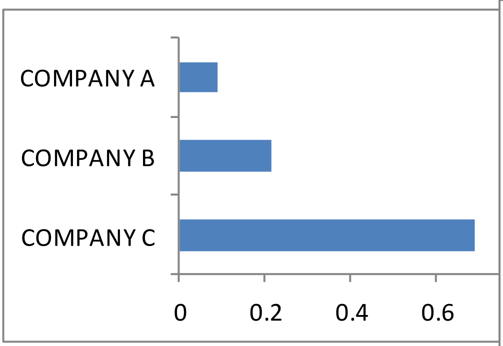


Figure 4: Relative weights for safety

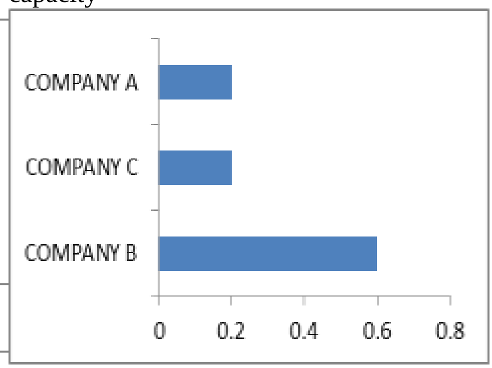


Figure 5: Relative weights for topography

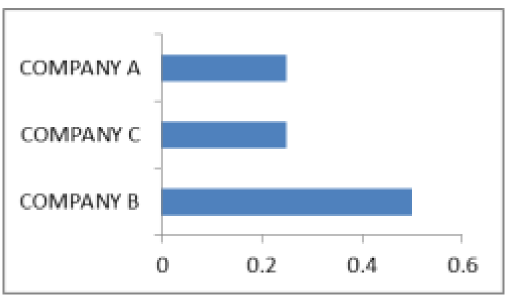


Figure 6: Relative weights for availability

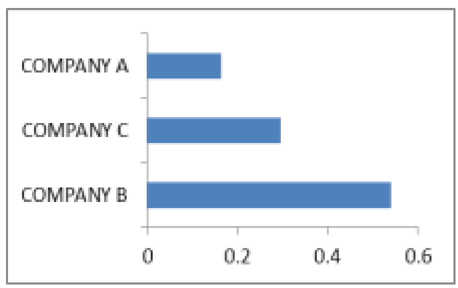


Figure 7: Relative weights for spares

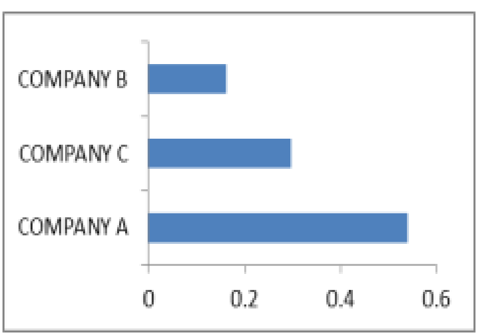


Figure 8: Relative weights for down times

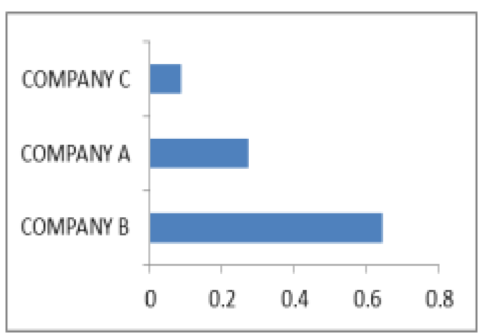


Figure 9: Relative weights for capital cost

### *Using Down Times Criteria for Comparison*

Using down times criterion, COMPANY A cement plant has the highest relative weight and COMPANY B has the smallest. Figure 9 shows the graphical illustration of the result.

### *Using Capital Cost Criteria for Comparison*

Based on the capital cost criterion, COMPANY B cement plant has the highest relative weight and COMPANY C has the smallest. This result is presented graphically in Figure 10.

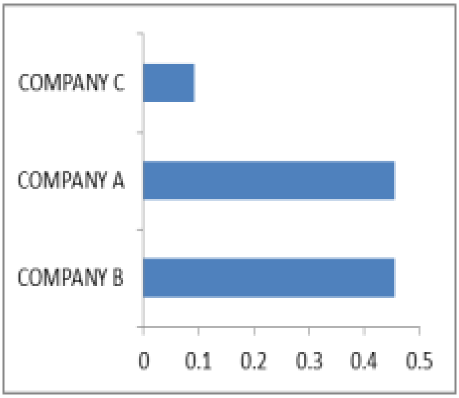


Figure 10: Relative weights for energy cost

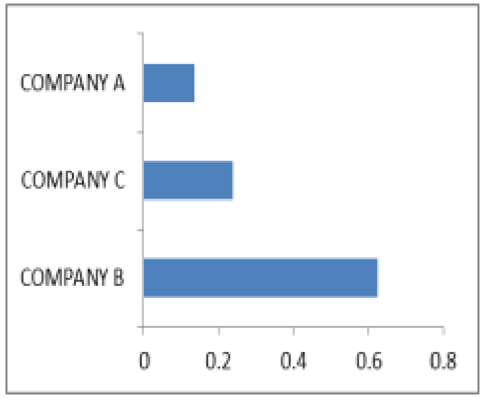


Figure 11: Relative weights for maintenance cost

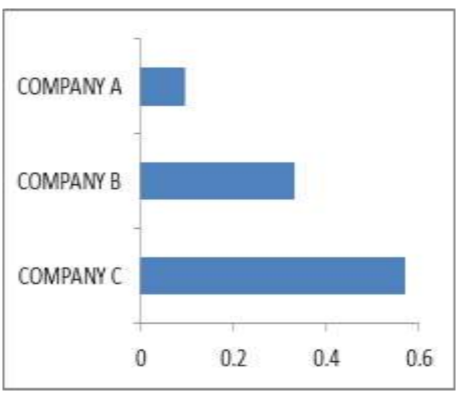


Figure 12: Relative weights for staff welfare

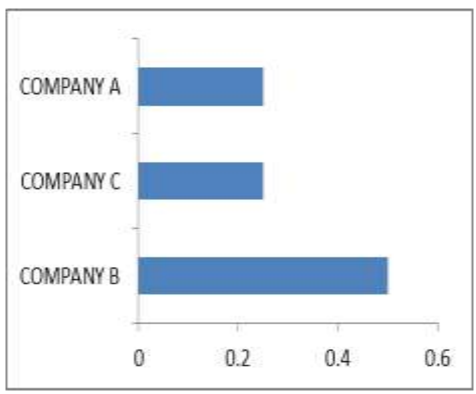


Figure 13: Relative weights for emission levels

### *Using Energy Cost Criteria for Comparison*

Based on the energy cost criterion, COMPANY B cement plant has the highest relative weight and COMPANY C has the smallest. This illustrated graphically in Figure 11.

### *Using Maintenance Cost Criteria for Comparison*

Based on the maintenance cost criterion, COMPANY B cement plant has the highest relative weight and COMPANY A has the smallest. This result is presented graphically in Figure 12.

***Using Staff Welfare Criteria for Comparison***

Based on the staff welfare criterion, COMPANY C cement plant has the highest relative weight and COMPANY A has the smallest. This is presented in Figure 13.

***Using Emission Levels Criteria for Comparison***

Figure 14 graphically illustrates that COMPANY B cement plant has the highest relative weight and COMPANY A has the least.

***Using Noise Level Criteria for Comparison***

Figure 15 presents COMPANY B cement plant has having the highest relative weight and COMPANY A has the smallest.

***Using Raw Materials Criteria for Comparison***

Figure 16 presents COMPANY C cement plant has having the highest relative weight and COMPANY A has the smallest.

***Using Dust Levels Criteria for Comparison***

Figure 17 presents COMPANY C cement plant has having the highest relative weight and COMPANY A has the smallest.

***Using Overall Composite Weights Criteria for Comparison***

For the overall composite weights, our analysis shows that COMPANY B cement plant is ranked top while COMPANY A is the one with the least weight. This is presented graphically in Figure 18.

## IV. Conclusion

The economic weight of cement industry calls for constant monitoring and strict adherence to regulation. A performance evaluation was carried out in this study for three cement plants located in Ogun state Nigeria. The methodology used for this work is the Analytic Hierarchy Process (AHP) which is based on multi-criteria pairwise comparison. Data was collected using questionnaires that were structured for cement plants based on the Saaty's rating scale. The results the analysis show that COMPANY B cement plant is ranked top followed by COMPANY C and then COMPANY A cement plants is least in descending order of overall composite weights. We also inferred that the difference between the overall composite weights between COMPANY B cement plant and COMPANY C is small coming at 0.405 and 0.381 respectively. COMPANY A is a little below at 0.214 which signifies that more should be done to improve on some significant plant operation standards. From the relative weights areas such as noise level, emission levels, staff welfare, energy cost, safety, ease of

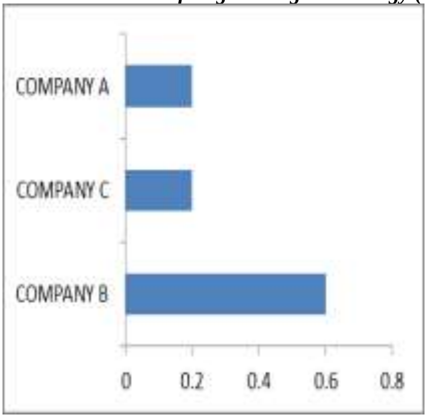


Figure 14: Relative weights for noise level

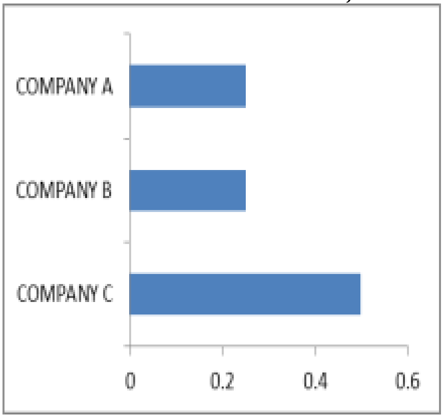


Figure 15: Relative weights for cost of raw materials

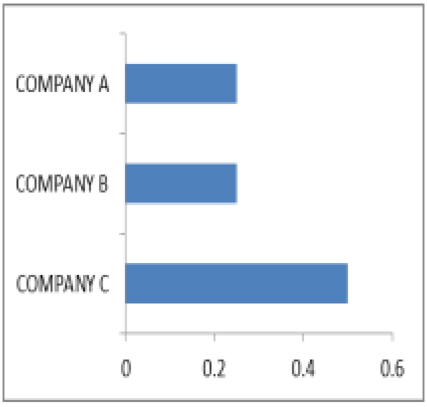


Figure 16: Relative weights for dust levels

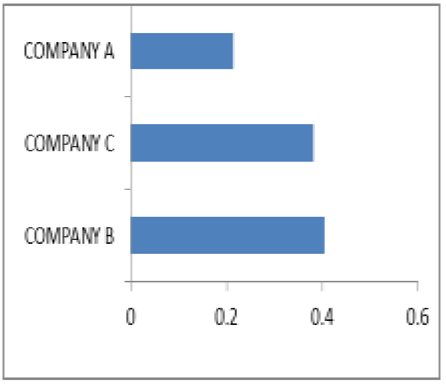


Figure 17: Illustration of overall composite weights

production setup and availability of spares parts should be improved. Production capacity should also be looked into and should be well scaled to accommodate all other production criteria and parameters. This study is however limited to Ogun State, Nigeria and can be extended to other regions in the country having cement industries. It should also be noted that most of the pairwise comparison done were based on expert judgment. Further studies will improve on this work and use actual values from plants. Our limitations were caused by difficulties in getting actual and accurate data from cement plant staff and related agencies. This can also be corrected if adequate time was given for proper sensitization of the cement plant management and agencies.

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# Improving Domestic Ergonomics: A Fuzzy-Based Model Approach

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***Abstract***: In this study a fuzzy logic model was adopted to assess the degree of Domestic Ergonomic Hazards (DEH) among women in the Southwest Nigeria. Three risk factors of weight (Kg), height of load (cm) and the handlers' arm reach (cm) were used. The leading objective was to provide an improved assessment ergonomics tool to Risk Assessment Filter (RAF). The algorithm of the fuzzy inference engine applied sets of 64 linguistic rules to generate the output variable in lifting/lowering risk. The Spearman's rank correlation value of 0.85 at the confidence level of 0.01, indicated no significant difference between the human predictions of DEH with the use of RAF tool and the model's predictions. The risk values and interpretations generated by the model were confirmed not just similar to, but with better information than, using RAF. The study proposed a fuzzy-based model for an enhanced domestic ergonomics among women than using RAF device. It is simple and can find its usefulness in household chores.

***Keywords*****:** domestic, ergonomics, hazards, women, fuzzy, model.

## 1. Introduction

Lifting, as defined by NIOSH [1], is a forceful movement requiring energy and muscle effort which stresses muscles, tendons and ligaments and increases forces on the spine. Lifting operations typically entail some risk factors that cannot be totally eliminated. In fact, no manual handling activity is completely safe. The physically demanding nature helps explain why strains and sprains are the most common type of injury among the group of workers involving in lifting related jobs. Lifting task may be considered hazardous if the imposed loads (forces) exceed the individual's strength and tolerance. Whereas the risk of injury is largely determined by the weight lifted. Hence, the amount of weight being lifted from floor level or above shoulder should be reduced and at neutral posture (body not twisted). Keeping arms fully extended, for instance, when lifting heavy loads may strain the forearm muscles. In a similar manner, holding objects at arm's length can also increase the load on the lower spine by 15 times the original weight. It is therefore safer to hold the object as close to handlers' body as possible to reduce the strain on arms and back [2-6].

Among the womenfolk, low back disorders are the most vital reported problem for those who work at construction sites and in industries where series of lifting related tasks are carried out. This has the tendency to influence the quality of work and health of female workers [7]. According to WHO [8] women, on the average, make up about 42% of the estimated global paid labour force population, making them indispensable contributors to national economies. In the developing countries, it is taken for granted that women will do most heavy lifting and carrying. In Nigeria, there are only few women in formal labour force [9].

Most women are involved in daily paid work and some of them are into lifting related, most especially in construction industry. Even at home where women tend to work more hours to make up the primary responsibility for family well-being, several casual lifting are engaged. Women's average lifting strength is only 50% of men's. Meanwhile physical load may exert greater strain on the average. Women are therefore more often exposed to some physical risks factors such as; repetitive movements, material lifting and awkward postures among others.

As part of its many efforts at helping employers, managers, safety officers, safety representatives, employees and others reduce the risk of injury from manual lifting, Risk Assessment Filter (RAF) relevant to: lifting and lowering; carrying for short distances; pushing and pulling; and handling while seated was developed by HSE [10].Using the filter, the guideline in Figure 1 helps to assess the task. It was however stretched that a more detailed assessment is necessary if: using the filter shows the activity exceeds the guideline figures; the activities do not come within the guidelines; there are other considerations to take into account; the assumptions made in the filter are not applicable; for each task the assessment cannot be done quickly. However for time or effort saving, it was stated that it may be better to opt immediately for the more detailed risk assessment. A full assessment of every manual handling operation however could be a major undertaking and might involve wasted effort [10]. Hence the need for more automatic, less human involvement and more detailed risk assessments tools that will allow expertise input into design process of which this study set out to achieve.

This study developed and validated a model capable of assessing the severity of injury risks involved in lowering and lifting operations carried out by Nigeria women. The objectives are to: provide an improved and less human involvement assessment tool to RAF; provide more information on the severity of injury risk involved in lifting/lowering operatios than may be achieved using RAF and; minimize injuries among women in household chores and other lifting related jobs.


**Fig. 1** Areas around the body within which loads may be lifted without risk for 95% of the Female population [11].

## 2. Materials and Methods

**2.1 Selection of lifting tasks and collection of variables for the model development.** In this study, three input variables were used. These variables are the major factors mentioned in lifting and lowering RAF guidelines. These include "weight", "handler height" and "handler arm reach". The applicable tasks considered were those based on; the load that is easy to grasp with both hands; the lifting operation that takes place in reasonable working conditions; and the handler in a stable body position [10]. The output variable, lifting/lowering injury risk was determined by fuzzy logic.

**2.2 Fuzzy Logic.** Fuzzy Logic algorithm was adoped in this study. The tool consists of heuristics rules that define the parameters of the focal problem. These include: data base, fuzzy rule base, fuzzy inference machine and defuzzification. Fuzzy Logic is applicable to artificial intelligence, control engineering, and expert systems [12]. The technique is functional in a wide range of applications designed to model the problem solving ability of a human experts. It imitates the logic of human thought and how a person would make decisions, only much faster [13]. Fuzzy logic was widely used when human evaluations and the modelling of human knowledge in risk assessment are needed [14,15]. Among many recent attempts with the use of fuzzy tool in risk assessments; [16] presented an adaptive neuro-fuzzy inference system to estimate maximum forces and moments being generated at the hip joint during lifting tasks using the duration of the lift, the height and mass of the subject, and the load as input variables; A fuzzy logic was adopted by Jelena and Dagan [17] for practical risk assessment of bridges under different hazards using the identified risks as input variables and bridge damage level as the output variable; Adeyemi et al., [18] developed a fuzzy-based expert system called the Pain Intensity Prediction Expert System (PIPES) to predict pain severity risk in shoveling-related tasks using scooping rate, scooping time, shovel load, and throw distance as input variables. An expert system called Musculoskeletal Disorders – Risk Evaluation Expert System (MSDs-REES) capable of assessing risk associated with manual lifting in construction tasks and proffer some first aid advices was earlier developed by same author using load, posture and frequency of lift as inputs and risk of low back pain as the output [19].

The fuzzyrules used were that of linguistic and in the form of "IF-THEN". According to Yager et al. [20], fuzzy IF-THEN rules allow to evaluate good approximations of desired attribute values in a very efficient way. It allows available experts' knowledge to be included. A single if-then rule assumes the form 'if x is Athen y is B'. The if-part of the rule 'x is A' is the premise, while the then-part of the rule 'y is B' is the conclusion [21].

**2.3 Domestic Ergonomic Hazards (DEH) evaluation with fuzzy logic model.** There are three steps involved in the development of the DEH evaluation model:

*2.3.1 Fuzzification of input variables and output risk values*. There are three general types of fuzzifiers to associate a grade to linguistic term, singleton fuzzifier, Gaussian fuzzifier and trapezoidal or triangular fuzzifier [22]. The data used in this model are vague, hence they were converted into fuzzy numbers. The crisp variables were transformed into grades of membership for linguistic terms of fuzzy sets. Intervals of 'handlers height' and 'arm reach' linguistic variables were carefully set, by the author, using lifting and lowering RAF guidelines. The female anthropometrical parameters of the variables were drawn from other authors and were modified to form the intervals. Sources of which include the reported; average female arm length of 67.725 (11.38) [23], forearm-hand length and upper arm of 45,00 (3.08) cm and 31cm (3.45) respectively [24], popliteal height of 47.7 (3.5) cm [25], Knee height of 56.9(3.1) [26], average standing shoulder height of 129.1(4.92) [27]. The weight classification linguistic variable was a modified version of the study results relating guidline weigth for lifting and lowering [10]. The output variable, risk level, was developed from the expert knowledge reported by Adeyemi et al., [19]. The numbers of MFs were determined by the author as well as the baselines. The researcher developed the system linguistic terms and intervals by detailing four linguistic terms to all the three input and the output variables as shown in Tables 1 to 4. Figure 2 to 5 are all the MFs for the input and output variables.

Table 1 Fuzzy set of input variable 'Handlers' height'

| Linguistic Terms | Interval |
|---|---|
| Shoulder height (SH) | 99.6,128.2,130.2,133 |
| Elbow height (EH) | 61.5, 98.1, 99.6, 128.2 |
| Knuckle height (KH) | 30.75,54.4,61.5, 98.1 |
| Mid lower leg height (MLH) | 0,27.2, 30.75, 54.4 |

*Modified version of the study results relating Anthropometry of South Eastern and South Western Females in Nigeria [26,27]*

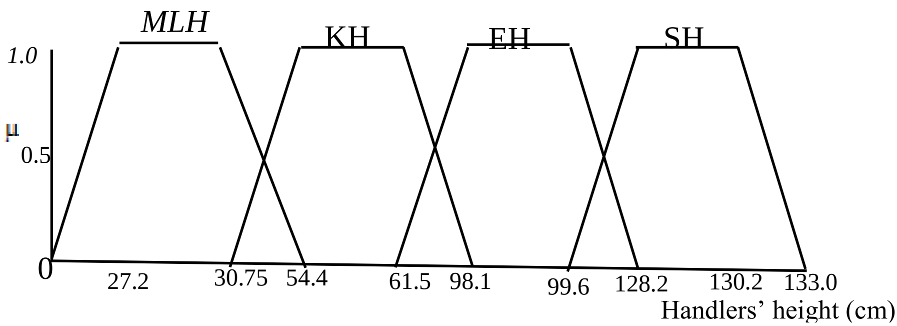


Fig. 2 All membership functions for the input variable 'Handler's height'

Table 2 Fuzzy set of input variable 'Weight'

| Linguistic Terms | Interval |
|---|---|
| No load (NL) | 0,0,0,0 |
| Light load (LL) | 0,3,5,7 |
| Midium load (ML) | 5,7,10,13 |
| Heavy load (HL) | 10,13,16,25 |

*Modified version of the study results relating guideline weight for lifting and lowering [10]*

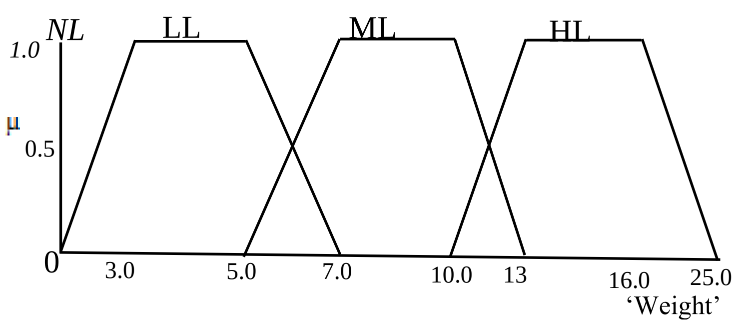


Fig. 3 All membership functions for the input variable 'Weight'

Table 3 Fuzzy set of input variable 'Handlers' reach'

| Linguistic Terms | Interval |
|---|---|
| No movement (NM) | 0,0,0,0 |
| Low arm movement (LAM) | 0,20,30,36 |
| Normal arm movement (NAM) | 30, 36, 45, 60 |
| Extended arm movement (EAM) | 45, 60,76, 85 |

*Modified version of the study results relating anthropometric parameters of South South and South West, Nigeria [24,28]*

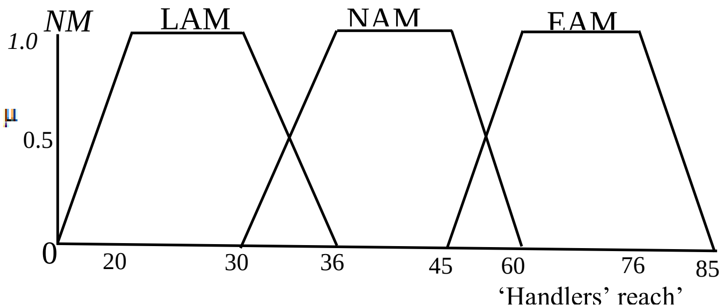


Fig. 4 All membership functions for the input variable 'Handler's reach'.

Table 4 Fuzzy set of output variable 'Lifting/Lowering Risk'

| Linguistic Terms | Interval |
|---|---|
| No risk (NR) | 0,0,0,0 |
| Low risk (LR) | 0,0,1,1.1 |
| Medium risk (MR) | 1,1.1,2,2.1 |
| High risk (HR) | 2,2.1,3,3.1 |

Adeyemi et al., [19]

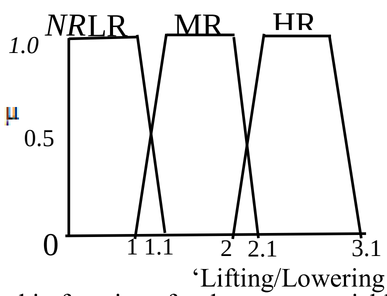


Fig.5 All membership functions for the output variable 'Lifting/Lowering Risk'

*2.3.2. Determination of application rules and inference method* A fuzzy rule is a simple IF-THEN rule with a condition and a conclusion. The relationship between heuristic, input and output parameters enabled the formation of 'If Then Rules'[29]. With the three inputs used in this study and each having four (4) variables, a rule base matrix, size of $4^3$ resulting in total sets of 64 matrices were achievable. The rules were "fired" by Mamdani's fuzzy inference method-the most commonly seen fuzzy methodology. The technique is intuitive, has widespread acceptance and is well-suited to human inputs [30].

The following rules show only a portion of the 64 possible linguistic rules designed and fired into the inference engine of the model:

- 1. If (HandlerHeigth is MLH) and (Weigth is NL) and (HandlerReach is NM) then (LiftingRelatedRisk is NR)
- 3. If (HandlerHeigth is MLH) and (Weigth is ML) and (HandlerReach is NM) then (LiftingRelatedRisk is LR)
- 19. If (HandlerHeigth is MLH) and (Weigth is ML) and (HandlerReach is LAM) then (LiftingRelatedRisk is MR)
- 48. If (HandlerHeigth is SH) and (Weigth is HL) and (HandlerReach is NAM) then (LiftingRelatedRisk is HR)
- 64. If (HandlerHeigth is SH) and (Weigth is HL) and (HandlerReach is EAM) then (LiftingRelatedRisk is HR)

*2.3.3. Defuzzification of risk value.* Defuzzificcation converts the fuzzy value obtained from composition into a "crisp" value. This process is often complex since the fuzzy set might not translate directly into a crisp value. Two of the more common defuzzificationtechniques are the centroid and maximum methods [31]. In the centroid method used in this model, the crisp value of the output variable is computed by finding the variable value of the center of gravity of the membership function for the fuzzy value.

**2.4 Model implimentation.** The model,DEH,was implemented in MATLAB®. MATLAB provides symbolic solution and a visual plot of result [32] and creation of user interfaces [33]. For each case, all the three variables were fuzzified by the application. Active MF were calculated according to rule table. The output, lifting/lowering risk, was defuzzified by calculating the center (centriod) of the resulting geometrical shape. This sequence was repeated for each scenario of lifting and/or lowering operations.

**2.5 Model Validation.** Three professionals qualified in the field of ergonomicsfrom academics environment drew out 16 scenarios and possible cases values using the lifting and lowering RAF and linguistic risk conclusions were drawn. The same variable values were run by the model to generate risk values and risk level predictions. The linguistic risks predicted by assessors using RAF were compared with that of the model.

For statistical confirmation, Spearman's Rank Correlation (SRC) coefficient was used. The RAF prediction which whichwas presented either "injury not likely" or "injury likely" were ranked "0" and "1" respectively. The model predictions were also categorized into two; those with "no risk" and those with "one level of risk or the other". These two categories were equally ranked "0" and "1" respectively. SRC was used to ascertain the strength of relationship between the two sets of data at the confidence level of 0.01. The SRC significance table was used to verify the significance of their relationship. Spearman's rank correlation coefficient ($r_s$) is a reliable and fairly simple method of testing both the strength and direction (positive or negative) of any correlation between two variables [34].

## 3. Results and Discussion

| Cases | Measurement | | | | | | HSE | Model | |
|---|---|---|---|---|---|---|---|---|---|
| | MLH (cm) | KH (cm) | EH (cm) | SH (cm) | Weigth (Kg) | Reach (cm) | Advise | Risk Value | Prediction |
| 1 | 25 | - | - | - | 6 | 40 | INL | 0.2 | NR |
| 2 | 25 | - | - | - | 9 | 40 | IML | 0.6 | LR |
| 3 | 24 | - | - | - | 5 | 80 | IML | 0.6 | LR |
| 4 | 5 | - | - | - | 3 | 110 | INL | 0.9 | MR |
| 5 | - | 57 | - | - | 14 | 76 | IML | 2.8 | HR |
| 6 | - | 54 | - | - | 12 | 38 | INL | 0.54 | LR |
| 7 | - | 62 | - | - | 15 | 71 | IML | 2.5 | HR |
| 8 | | 43 | | | 6 | 115 | INL | 0.4 | LR |
| 9 | - | - | 98 | - | 14 | 35 | IML | 1.4 | MR |
| 10 | - | - | 92 | - | 13 | 72 | IML | 2.5 | HR |
| 11 | - | - | 97 | - | 20 | 37 | IML | 1.6 | MR |
| 12 | - | - | 102 | - | 7 | 68 | INL | 0.4 | LR |
| 13 | - | - | | 125 | 15 | 42 | IML | 2.4 | HR |
| 14 | - | - | | 129 | 6 | 38 | INL | 1.5 | MR |
| 15 | - | - | | 132 | 4 | 82 | IML | 2.2 | HR |
| 16 | - | - | | 137 | 10 | 75 | IML | 1.5 | MR |

INL= Injury Not likely,IML = Injury most likely, MLH = Mid lower leg height, KH = Knuckle height, EH = Elbow height , SH = Shoulder height

**3.3 Model performance.** Sixteen scenarios and possible cases formulated by ergonomics professional are shown in Table 5 on each of the cases the height, arm reach and mass of load lifted by handlers were considered by the assessors using RAF in Figure 1. The linguistic predictions is as indicated. The same data were run with the model to generate risk values which were interpreted using Table 4 and the results are shown. The interpretations of the assessors and that of the model when compared shows that in 10 out of the 16 samples (63%) where assessor predicted "injury most likely" using RAF, the model also predicted one level of injury or the other in all the 10 cases. This represented 100% agreement using the two assessment tools. In the remaining 6 cases (37.5%) where assessor predictted "injury not likely" the model however predicted "low risk" in three of such cases (50%), "No risk" in one (25%) and "medium risk" in two (33.3%).

**3.4 Statistics Analysis Tests.** Spearman's rank correlation coefficient of 0.99 was obtained when the RAF predictions were compared with the predictions of the model. This shows a strong strength of relationship between the output of the two assessment tools. With the SRC value of 0.85 obtained using SRC table at the confidence level of 0.01, there is greater than 99% chance that the relationship is significant. Hence there is no significant difference between the RAF injury suggestion and the model predictions.

**3.5 Discussion.** The study adopted fuzzy tools to evaluate risk connected with lifting and lowering objects based on three input variables; handler height (cm), weight of object (kg) and the handler arm reach (cm). One of the advantages derived with the use of this approach is that, fuzzy logic, unlike Boolean logic which does not provide the means to identify an intermediate value. Fuzzy logic handles the expression of vague concepts. For the fuzzy systems, truth values (fuzzy logic) or membership values (fuzzy sets) are in the range [0.0, 1.0], with 0.0 representing absolute falseness and 1.0 representing absolute truth [31]. The fuzzy rules of this format contains linguistic variables which is easier for users understanding result for users' easier comprehension of risks severity connected with the lifting attempt. For example stating ordinarily by the assessors that 'injury is most likely' in scenario 5 where a handler lift a 14kg weight from her 57cm knuckle height and her hand extended to 76 cm, may not be enough information needed for him to take necessary decision to avoid likely resulted injuries. However with the use of this model, additional information useful for taking right decision are provided. The model clearly mentioned that the lifting or lowering of such load will not only lead to injury, but that the risk involve is very high. The magnitude of the risk involved in this information provided by the model is quite easy to understand and help the handlers avoid vital injury that may be resulted.

The model provided good results comparable with the human assessors' opinions when selected scenarios were run in the model. In all the cases (100%) where assessor used RAF to predict either "No injury" or "Likely injury", the model interpretations also predicted one level of injury or the other only with additional information.

The fuzzy approach in this study considered inherent uncertainties of the membership classification process, such as in the classification of a handler reach with 45.5cm and another one with 46.1cm, which could be relegated both as NAM (Normal arm movement) and EAM (extended arm movement) at the same time. These arm movement (45.5 cm and 46.1 cm) simultaneously fit into the two membership functions but with different degree of memberships and interpretation of results.

A risk assessment model can be considered successful when it has the capacity at following human expert predictions and fulfilled the objectives for which it was developed. Hence success can be assigned to this model because it mimics the predictions of the human assessors with improved information that can prevent injuries and enhance safety and health of women handlers. The model can find its application among women in household chores and in workplaces where women are engaged in lifting or lowering tasks.

There are however a number of limitations that should be aware of for future efforts. One of which is the fact that posture of the individuals was not included within the analysis but forms a significant lifting risk assessment variable that could be covered. Future efforts may consider inclusion of such variable and the development of similar model for the menfolk.

## 4. Conclusion

In this study a fuzzy logic based model was adopted to evaluate the domestic Ergonomic hazards in lowering and lifting objects based on three risk factors of weight, height of load and the handler arm reach. The model provided a structure that gives vital information on the risk level attached to material handling at household chores where women are engaged in lifting-related tasks. The validation result indicated that the injury risk values and the linguistic interpretations provided by the model were confirmed the same with the ones provided by the human assessors (with the use of risk assessment filter) and with added improved information. Adopting this technique will reduce injury related medical bills and enhance safety and health of the womenfolk while handling materials in domestic duties.

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# Analysis of Ship Operation Safety within the Harbor under the Effect of Wave

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***Abstract***: This research present the wave impart analysis on the operational safety of cargo ship in harbor and it effect on a mooring line system. From the analysis using MATLAB program the wave formed velocity in horizontal direction show a 1% decrease from (0.1 to 8m) of the water depth and the velocity in vertical direction show 2% increase from (0.1 to 8m) of the water depth. The acceleration in horizontal direction show 2% increase from (0.1 to 8m) of the water depth and the acceleration in vertical direction show 2% decrease with from (0.1 to 8m) of the water depth. The wave load on the mooring line between two anchors (A and B) of 1059m suspended length (Ls) is 200KN with horizontal restoring force at the Fairland (TH) of 1200KN which increase the tension by 250KN and causes the Fairland shift by 0.54m. This resulted to a reduction in mooring anchor XB to 498.96m and XA to 500.04m. The analysis also shows that the rate of water particle velocity and acceleration due to wave effects decrease with increase water depth, and the combined effect will cause damage to the catenary mooring line in extreme significant waves height and period. Sudden and critical tension on the chain and anchor A and B may set under this environmental load. The stability and dynamic positioning of any floating vessel is essential during offshore activities in the harbor. Therefore, it is necessary to carryout mooring system analysis and monitoring for safe ship operation under environmental wave load in the Harbor.

***Keywords*** –SWATH, Resistance, Propulsion, Catamarans, Hull, Velocity and Vessel

## 1. Introduction

The function of a harbour is to provide safe anchorage for vessels and to facilitate smooth transfer of cargo between ship and adjoined land. Assured harbour tranquility is not on essential for safe anchorage, but it is also important for efficient port operation. Essentially, harbor tranquility reduces to the excitation of ships moored at anchorage or along a wharf and optimizes the mooring forces. Larger ships may not experience wave agitation to the wind-waves, whereas a small boat may be violently swung by the same wave [1].

In the viewpoint of port operation, the relationship between ship motion and cargo handling works as well falls in the judgment of harbor tranquility. Hence the use of constant tension winches and the stiffness and friction of the fenders, can have a very large influence on the resulting ships motions, the surge motion external forces from wind, waves and or currents [2].

## 2. Description of ship behavior at berth.

The movement of a moored ship at berth can be described by the three translator movements, namely surge, sway and heave, and the three movement of rotation, known as pitch, roll and yaw. This project is to determine the effective waves forces acting on the ship mooring line during anchorage at harbor; to determine the various load on ship at Harbor; to determine mooring effect on ship at harbor and to determine safety precautions for ship under wave.

### 2.1. Basic definitions of forces acting on a vessel at Harbor

Some forces act on a vessel at harbor. The forces are berthing forces, current force, seismic force, active earth pressure, mooring forces. The forces are described as follows:

#### 2.1.1. Berthing Force

Horizontal forces act on the berth, whenever a vessel impacts on the berth anytime of the year. The strength of this force wholly depends on the energy in motion that can be absorbed by the fender system. The design vessel will be contacting the fenders at an approach angle of 100. Therefore, the impact as a result of berthing of the ship is at quarter point. When the berthing takes place, the fender system absorbs energy in motion and converts it into strain energy, thereby passing on a reaction force to the structure and the reaction force for which the berth is to be designed can be revealed from this process and deflection-reaction diagrams of the fender system selected [3].

#### 2.1.2. Current Force

Currents can be described as the relatively constant motion of water caused by tidal action, wind drag, or river discharge. The most common currents considered in offshore structural analysis are tidal currents and wind drift currents. The later is generated from the drag of local wind on the surface of the water. The tidal and wind drift currents are regarded as horizontal and varying with depth. When vessel is fully loaded, pressure usually applies to the part of the vessel below the waterline dues to currents. The part of the vessel covered is approximately equal to wv2/2g per square meter of the part, where v is the velocity in m/s and w is unit weight of water in t/m2. The vessels usually berths parallel to the current. On harbor parallel to the direction of the water current, there are two types of ocean current, the surface circulation current and the deep circulation current [4].

### 2.1.3. Seismic Force

In areas susceptible to seismic disturbance horizontal force equal to a friction of the acceleration of gravity times the weight applied as its centre of gravity should be taken. The fraction will depend upon the likely seismic intensity of the area and shall be taken in accordance with IS: 1893-2002. The weight to be used is the total dead load plus one half of the live load [5].

### 2.1.4. Active Earth Pressure

This type of force is applicable only if the berth has a retaining wall at the landside, thus retains the earth. Active earth pressure is experienced in situations where the wall moves sufficiently away from the backfill by translatory motion, rotation about the base or their combination, which reduces lateral pressure of the backfill. Active earth pressure does not occur in jetty or pier.

### 2.1.5. Mooring Force

The mooring loads are the lateral loads caused by the mooring lines when they pull the ship into or along the dock or hold it against the forces of wind or current. The load on ropes caused by winds or currents, acting on the ship during berthing cannot be estimated with accuracy. Factors such as tensioning of the rope and its angle to the berthing line are considered during such estimation exercise. Thus, mooring force will be two types; Wind force and Current force [6]. Ships are moored at berth, when the followings below are available.

- Mooring lines connecting ships to berths
- Bollards and storm bitts on shore
- Mooring hooks on mooring and breasting dolphins.
- Fenders between ship and berth
- Mooring winches and bollards that is onboard the vessels to be moored.

### 2.1.6. Wave force

The periodic undulation of the sea surface is known as waves. The complexity of motion of the waves is a major challenge to workers in the ocean environment. Waves cause fatigue type of loading on offshore and exposed coastal structures. They adversely affect coastlines and harbor facilities and induce violent motions in moored ships and floating structure [7].

## 2.2. Criteria and Framework of Vessels at Harbor

In analysis of ship operations at harbor, port and harbor risk assessment criteria, frequency criteria, defining the framework for marine risk assessment

### 2.2.1. Port and Harbor Risk Assessment Criteria

The risk assessment criteria for port and harbor need to be known, so as to provide guidance for the assessment exercise. They are recommended because they provide a consistency of standard for all ports and harbors. However, consideration should be given to modification of one scale should circumstances at a particular harbor or port demonstrate the need [8].

### 2.2.2. Frequency Criteria

The frequency component of risk is usually considered based on per-movement basis or a simple per-annum basis. Where ports or harbors have a larger number of movements, a per-movement scale can be considered as this provides a simple set of criteria for reporting safety performance once the safety management system is established. Risk and safety management software can be used to detect a per-movement and a per-annum frequency scale at any stage.

### 2.2.3. Defining the Framework for Marine Risk Assessment

The framework for any marine risk assessment logically needs to follow the established Formal Safety Assessment (FSA) marine incident categories that are relevant to assessment in a port or harbour. These are Collision, Contact (which can include a sub-category of Berthing Contact), Grounding, Loss of Hull Integrity, Fire/Explosion, Equipment Failure (Often a cause of other accident categories) and Personal Injury.

Collision and contact differentiation as incident categories is vital. The definition of collision is obvious. Contact is associated with incidents involving the vessel striking something fixed, such as a navigation aid or heavy landing on a berth, or a bar harbor, or a bridge structure or deck.

The port or harbor then needs to be categorized into appropriate areas for the risk assessment. Areas are selected partly around natural topographical features, such as channel extents, but also very much around the marine activities associated with an area. Selection of areas is important if the Port and Harbor Safety Management System is considered. Under the Port and Harbor Safety Management System, risk can be expressed by area if wanted and risk management can also be targeted by area. Areas are depicted on the chart as Area A; Area B, etc, and for a key categorization for the hazard identification process.

Vessel types then need to be defined associated with the trades of the port or harbor. It is appropriate to consider primary and secondary types during such definition exercise. For example, a primary category of "Tankers" can have sub-categories of LNG; Chemical (MARPOL Annex II); Product.. Passenger vessels can also be categorized in the same way, as can leisure craft in a harbor with different leisure activities ongoing [9].

### 2.3. Hazard Identification Process

Hazard identification is the most important step of risk assessment process. An overlooked hazard is more likely to introduce error into the overall risk assessment of a port or harbor, than an inaccurate assessment of frequency or consequence identified hazards. Errors made in assessing consequence and frequency of hazards can cancel each other out over the full spectrum of incidents The omission of a hazard can result in an underestimation of the overall risk profile. Moreover, important risk control may not be introduced to properly manage the risk, resulting in an accident waiting to happen [10].

## 2.4. The Port and Harbor Safety Management System

The successful introduction of a working Port and Harbor Safety Management System is not a small task and the time-scales needed to achieve this should not be underestimated. From experience of harbors and ports generally, the process often involves organizational change which will only occur if undertaken in a measured and planned way [11].

Policy is set at the top of the organization, with identified roles and responsibilities to discharge the policy being designed next. The new or changed risk control options and procedures originating out of the risk assessment process then follow. A key component is intelligence, which is kept refreshed by ongoing consultation with users and from the results of audit or review. Feedback from users of the safety management system significantly enhances intelligence, but only if the climate within or between organizations facilitates the information flow. If the feedback information flow is good, then the safety management system can provide an open and proactive feed-forward flow of information to all [12].

## 2.5. Navigation safety policy A D V I

This section takes the form of a declaration of the overall navigational safety policy objectives. Typical stated objectives are [11]:

i. Comply with all legal duties and responsibilities for the regulation of vessel traffic and the safety of navigation.
ii. Develop and maintain an effective Safety Management System based on the continuing assessment and mitigation of risk.
iii. Maintain access to port services, by ensuring the provision of appropriate pilotage, traffic management, towage, and berthing services.
iv. Develop a consensus for safe navigation through stakeholder input.
v. Ensure that suitable anchorages, mooring locations and the best channels for navigation, are determined, marked, monitored and maintained.
vi. Sustain its harbour management functions in respect of hydrographic surveying, navigation, dredging, and the provision and maintenance of navigation aids.
vii. Remove sunken vessels and other obstructions that are, or may become, an impediment to safe navigation
viii. Promulgate relevant navigational, tidal and weather information to all port users as determined by the risk assessment.
ix. Facilitate the leisure use of the port, maintaining and protecting the rights of the public to access its waters for leisure use, whilst complying with the various navigational safety measures that may be in force.
x. Create awareness and motivation of all port users with respect to safety and the protection of the environment.
xi. Publish and maintain contingency plans to cover emergency situations relating to the safety of life, property or the environment.

xii. Maintain appropriate emergency and oil spill response capabilities.

xiii. Ensure that all port or harbor operational staffs are trained to recognized standards and have appropriate experience for their roles and duties.

xiv. Ensure that working craft, including tugs, pilot boats and work boats are fit for their purpose and operated to appropriate safety standards.

xv. Review regularly duties and powers required to support and maintain an up-to-date set of bylaws in respect of navigational safety and enforce them so as to effectively regulate and facilitate harbor use.

xvi. Keep under review the cost effectiveness of modern

## 3. Material and Methods

This research will focus on methods use in the analysis of waves acting on ship within the harbor. Mooring equation will also be utilized in calculation of the forces and tension acting on mooring line. Such exercise will be facilitated using a MATLAB software.

### 3.1. Wave Theory

There are many wave theories that are useful in the design of offshore structures such as linear/airy wave theory, second-order stroke wave theory, fifth-order stroke wave theory and the stream function theory. This research is focus on linear/airy wave theory [13]. The parameters that are needed in describing any wave theory are:

i. Period (T), which is the time taken for two successive crests to pass a stationary point [14].

ii. Height (H), which is the vertical distance between the crest and the following trough [14].. For a linear wave, the crest amplitude is equal to the trough amplitude, while they are unequal for a non-linear wave [14].

iii. Water depth (d), which represents the vertical distance from the mean water level to the mean ocean floor [14]. For wave theories, the floor is assumed horizontal and flat [14].

iv. Wavelength (L), which is the horizontal distance between successive crests [14].

v. Wave celerity or phase speed (c), which represents the propagation speed of the wave crest [14].

vi. Frequency (f), w which is the reciprocal of the period [14].

vii. Wave elevation (β) which represents the instantaneous elevation of the wave from the still water level (SWL) or the mean water level (MWL) [15].

viii. Horizontal water particle velocity (u), which is the instantaneous velocity along x of a water particle [14].

ix. Vertical water particle acceleration (G), which is the instantaneous acceleration along x of a water particle [14].

x. Vertical water particle acceleration (G), which is the instantaneous acceleration along y of a water particle [14].

xi. For the linear wave theory, the wave has the form of a sine curve and the free surface profile is written in the following simple form: $\mu = a \sin (kx - wt)$ [14].

xii. Crest the top of the wave [14].

### 3.2. Linear/Airy Wave Theory

The simplest, but very useful wave theory is the linear or small amplitude wave theory, which assumes that the wave amplitude is small compared to the wavelength [16].

The linear wave theory is also called the first-order theory because one can neglect terms that are above first order when expanding the solution in a perturbation series. The wave profile are then assumed to be expanded in power series of a non-dimensional perturbation parameter, £, in terms of the wave slope at the zero-down crossing of the wave [17].

### 3.3. Finite Water Depth

Velocity potential

$$\emptyset = \frac{g\zeta_a \cosh k(z+d)}{\omega \cosh kd}\cos(\omega t - kx) \qquad (1)$$

Dispersion relation

$$\frac{\omega^2}{g} = k\tanh kd \qquad (2)$$

Wave length $L_0[(\frac{2\pi d}{L_0})]^{1/2}$ (3)

Wave elevation $\zeta = \zeta_a \sin(wt - kx)$ (4)

Dynamic pressure

$$P_D = \frac{\mu y\zeta_a \cosh k(z+d)}{\cosh kd}\sin(\omega t - kx) \qquad (5)$$

Velocity in x -

$$u = \omega\zeta_a \frac{\cosh k(z+d)}{\sinh kd}\sin(\omega t - kx) \qquad (6)$$

Direction Velocity in z –

$$w = \omega\zeta_a \frac{\sinh k(z+d)}{\sinh kd}\cos(\omega t - kx) \qquad (7)$$

Direction Acceleration in x–axis

$$a_x = w^2\zeta_a \frac{\cosh k(z+d)}{\sinh kd}\cos(\omega t - kx) \qquad (8)$$

Acceleration in z- axis

$$a_z = -w^2\zeta_a \frac{\sinh k(z+d)}{\sinh kd}\sin(\omega t - kx) \qquad (9)$$

Where; Angular wave ω = 2π/T, Wave number k = 2π/λ, Λ is the wave length, T = wave period, Ca = wave amplitude, g = acceleration of wave due to gravity, t = time, x = direction of wave propagation, z = vertical coordinate, d = water depth, Total pressure in the fluid $= p_d - pgz + p_o$ and $p_0$ = atmospheric pressure

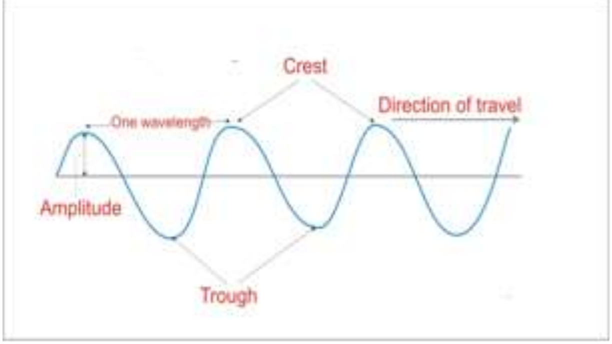



Figure 1: Transverse wave [17]

### 3.4. Catenary Mooring Line Equation

Catenary moorings are common in oceanographic, metrologic and offshore applications. These systems accommodate current, wind, tides, and wave induced deformations by lowering and lifting excess line to and from the sea floor. It can play an important role in the dynamic response of the system [20].

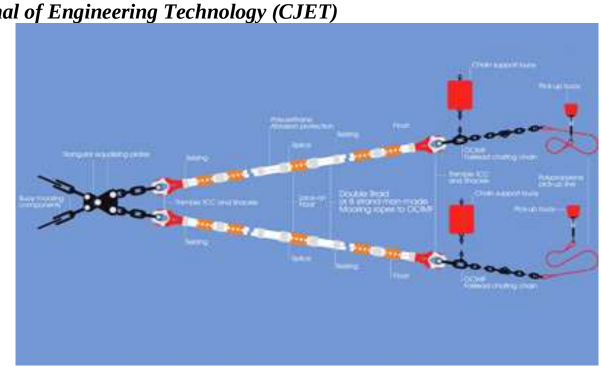


Figure 2: Single point mooring system [21].

A single point mooring system is used to connect all the lines to a single point. It links sub-sea manifolds connections and weather running tankers, which are free to rotate 360 degrees. A buoy, mooring and anchoring elements are the single point system. Tension acting on the mooring rope can be calculated using formulas as follow [22].

Suspended line length

$$Ls = a\,Sinh\left(\frac{x}{a}\right) \quad (10)$$

Vertical dimension (depth)

$$h = a\left\{cosh\left(\frac{x}{a}\right) - 1\right\} \quad (11)$$

Where parameter $a = \frac{T_H}{W}$

Using line tension at the platform

Tension at the top is

$$T = W\frac{(L^2s + h^2)}{2h} = \sqrt{{T_H}^2 + {T_z}^2} \quad (12)$$

$$T_H = T\cos(\theta_w) \quad (13)$$

Maximum tension $T_{max} = T_H + wh$ (14)

We have the minimum limit length

$$L_{min} = \sqrt[n]{2\frac{T_{max}}{wh} - 1}$$

Requirement $T_{max} \leq T_{br}$ (15)

(Breaking strength/tension in mooring line).

$$X = L - Ls + x \quad (16)$$

$$X = L - h\sqrt{\left( + \frac{2a}{h} + \propto \cos -^1\left[1 + \frac{h}{a}\right]\right.} \quad (17)$$

$$X = L - h\sqrt{\left[1\ \frac{2T_H}{wh} + \frac{T_H}{w}\right] + \cosh -^1\left[1 + \frac{wh}{T_H}\right]} \quad (18)$$

$$X = cosh^{-1}\left[1 + \frac{h}{a}\right] \quad (19)$$

Definition of parameters

Ls = Suspended line length

h = Vertical dimension (depth)

$T_H$ = Horizontal restoring force applied by the mooring lines

$T_z$ = Vertical component of tension

$T_{max}$ = Maximum tension

T = Tension at the top

W = Weight per unit length of cable in water

$L_{min}$ = Minimum line length

a = Horizontal dimension

Sin h and Cos h are parabolic function

**Wave parameters**

Wave heights (H) - - - 2m

Water depth (d) - - 8m

Wave period - - - 6.5m

For shallow water

6.5x8.86

$L = {}^{T}/\sqrt{gd} = \frac{6.5}{\sqrt{9.81 \; x \; 8}} = 6.5\text{x}8.86 = 57.6$ m

For deep water

$L_o = {}^{gT^2}/_{2\pi} = \frac{9.81 \; x \; (6.5)^2}{2 \; x \; \pi} = 65.97m = 67m$

Intermediate water depth

$I = L_o \left[\left(\frac{2\pi d}{L_o}\right)\right]^{1/2} = 67 \left[\left(\frac{2\pi \; x 8}{67}\right)\right]^{1/2}$

= 58m

Table 1 Wave parameters

| Parameter | Formula | Calculation | Result |
|---|---|---|---|
| Wave frequency (w) | $\frac{2\pi}{T}$ | $\frac{2 \; x \; 3.142}{6.5}$ | $0.97 \; {}^{rad}/_{sec}$ |
| Wave length (λ, L) | $L_o \left[\left(\frac{2\pi d}{L_o}\right)\right]^{1/2}$ | $67 \left[\left(\frac{2 \; x 3.142 \; x \; 8}{67}\right)\right]^{1/2}$ | 58m |
| Wave speed (c) | $\frac{L}{T}$ | $\frac{58}{6.5}$ | 8.92m/s |
| Wave number (K) | $\frac{2\pi}{L}$ | $\frac{2 \; x \; 3.142}{58}$ | 0.11 |
| Amplitude (a) | $\frac{H}{2}$ | $^{2}/_{2}$ | 1 |
| Time (t) | $\frac{3T}{4}$ | $\frac{3 \; x 6.5}{4}$ | 4.88(sec) |
| Frequency (f) | $\frac{1}{T}$ | $\frac{1}{6.5}$ | 0.15 $H_2$ |
| Wave length (L) | $^{C}/_{F}$ | $\frac{8.92}{0.15}$ | 59.47 = 60m |

Table 2: Parameters of wave calculated

| Parameters | Values | Units |
|---|---|---|
| Wind velocity | 0 | (m/s) |
| Wave length (λ, L) | 58 | (m) |
| Wave number (K) | 0.11 | |
| Wave length (L) | 60 | (m) |
| Amplitude (a) | 1 | (m) |
| Time (t) | 4.88 | (s) |
| Wave speed (C) | 8.92 | $(\frac{m^2}{s})$ |
| Wave frequency (w) | 0.97 | (rad/sec) |
| Wave height (H), (x) | 2 | (m) |
| Water depth(d) | 8 | (m) |
| Wave period (T) | 6.5 | (s) |
| Density of water $(e_s)$ | 1.025 | $Kg/m^3$ |
| Frequency (f) | 0.15 | Hz |
| Design current speed $U_C$ | | |

**Velocity $U_x$ Direction**

$$U_x = w\zeta_a \frac{\cosh\ K\ (Z+d)}{simhkd}\ sim\ (wt-kx)\ = 1.08\ m/s$$

**Velocity in Z Direction**

$$U_z = w\zeta_q \frac{Simhk\ (Z+d)}{simhkd} \cos\ (wt-kx) = 1.76\ m/s$$

**Acceleration in x Direction.**

$$A_x = w^2\ \zeta_q \frac{\cosh K\ (z+d)}{simhkd} \cos (wt-kx) = 1.32\ m/s^2$$

**Acceleration in Z Direction**

$$A_z = w^2\ \zeta_q \frac{simhk\ \ (z+d)}{simhkd} sim\ (wt-kx) = 0.58\ m/s^2$$

**Mooring Data**

This mooring system lines are designed to stabilize the portion for the storage or fuel offshore with design specification of net Norske veriths.

Length of anchor chain (L) = 500M

Number of anchors used = 2 anchors

Horizontal pretension TH = 150KN

Weight of anchor in water (W) = 1000 N/M

Height of water depth (h) = 100m

Length of work barge LP = 60m

Breadth of work barge $B_p$ = 25m

Height of work barge HP = 4m

From the figure, the distance is (2x +Lp) in

Using expression

X = L – Ls + x

Where $L_2^2 = h^2 + 2ha$

$$a = \frac{TH}{W} = 150m$$

$$L_s^2 = (100)^2 + 2\ x\ 100\ x\ 150$$

Ls = 200m

Calculate for the value of x the suspended length

$$L_s = a\ smh\ \left(\frac{x}{a}\right)$$

X = 199.5m

X = L – Ls + X = 499.5m

Distance between two anchor A & B (2x + Lp) m = 1059m

Hence

The distance from anchor A and B is = 1059m

$L_{min}$ = 0.00697m

Vertical force at the fairlead Tz = WLs

Tz = 1 x 200 = 200KN

Tension at the top

$T = \sqrt{T_h^2 + L_s^2}$ = 250 KN

:. Max tension at the top

Tmax = TH + Wh

Tmax 250 KN

a = $L_s^2$ = $\frac{(L^2 - h^2}{2h}$ = 1200m

new a = 1200m

New Th = horizontal pretension

$T_h$ = aw = 1200 KN

New $X_a$ due to mo vena is from

$\frac{L_s}{a} = 5m\,h\left(\frac{XA}{a}\right)$

Xa = 500.04 m

Hence the Fairland moved a distance (500.04 – 499.5) m = 0.54m

The initial pretension

TH = 1200 KN

X = 300.54m

This movement causes reduction in $X_B$ by 499.5 – 0.54, XB = 498.96m

New $X_B$ for anchor B the effective environmental force on the anchor A that will cause this now $X_B$ = 499m on anchor B.

## 4. Results and Discussions

The water particle velocity and acceleration are calculated using a MATLAB program.

Table 3: Combined wave and current velocity

| Water depth | Velocity x direction ux | current velocity uc | Total Velocity Ut = Ux + Uc |
|---|---|---|---|
| 0 | 1.74 | 17.40 | 19.14 |
| -1 | 1.72 | 17.40 | 19.12 |
| -2 | 1.69 | 17.40 | 19.09 |
| -3 | 1.63 | 17.40 | 19.03 |
| -4 | 1.55 | 17.40 | 18.95 |
| -5 | 1.46 | 17.40 | 18.86 |
| -6 | 1.35 | 17.40 | 18.75 |
| -7 | 1.22 | 17.40 | 18.62 |
| -8 | 1.08 | 17.40 | 18.48 |

Table 4: Velocity and acceleration values

| Water depth | Horizontal Velocity Ux | Vertical velocity Uz | Horizontal acceleration Ax | Vertical acceleration Az |
|---|---|---|---|---|
| 0 | 1.74 | 0.02 | -0.04 | 0.94 |
| -1 | 1.72 | 0.13 | -0.22 | 0.93 |
| -2 | 1.69 | 0.23 | -0.40 | 0.91 |
| -3 | 1.63 | 0.33 | -0.58 | 0.88 |
| -4 | 1.55 | 0.43 | -0.75 | 0.84 |
| -5 | 1.46 | 0.52 | -0.91 | 0.79 |
| -6 | 1.35 | 0.61 | -1.06 | 0.73 |
| -7 | 1.22 | 0.69 | -1.20 | 0.66 |
| -8 | 1.08 | 0.76 | -1.32 | 0.58 |

Table 5: Horizontal restoring force and draft

| Draft d/L (m) | Horizontal restoring force applied by the mooring line tension $T_H$ (KN) |
|---|---|
| 100 | 240 |
| 200 | 480 |
| 300 | 720 |
| 400 | 960 |
| 500 | 1200 |

Figure 3: Graph showing increase in total velocity and increase in water depth

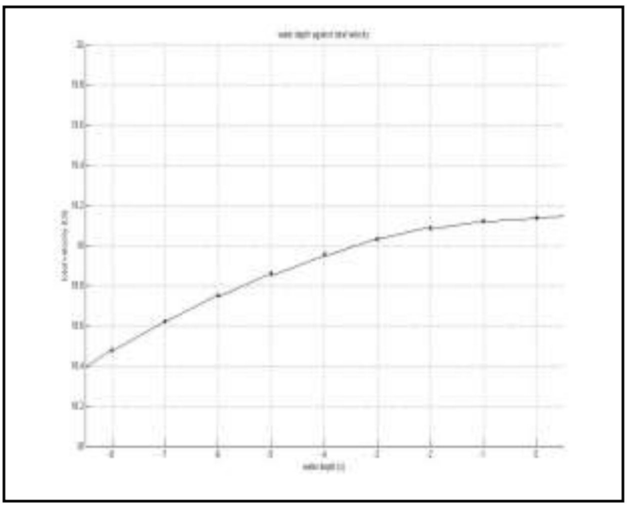


Figure 4: Graph showing increase in horizontal and vertical acceleration with increase in depth

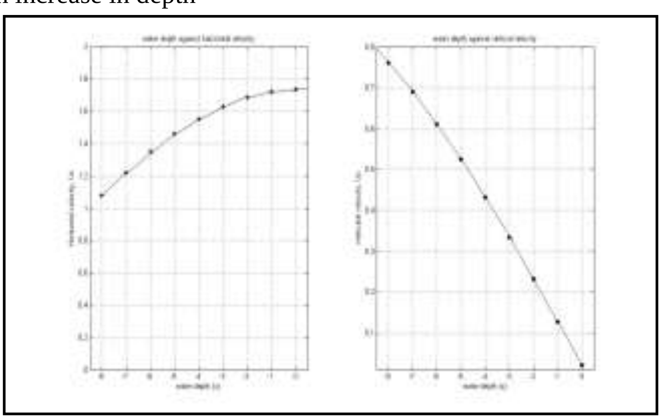
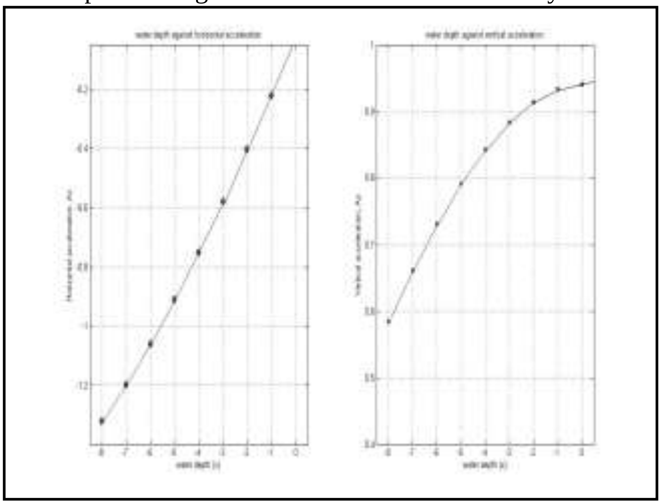
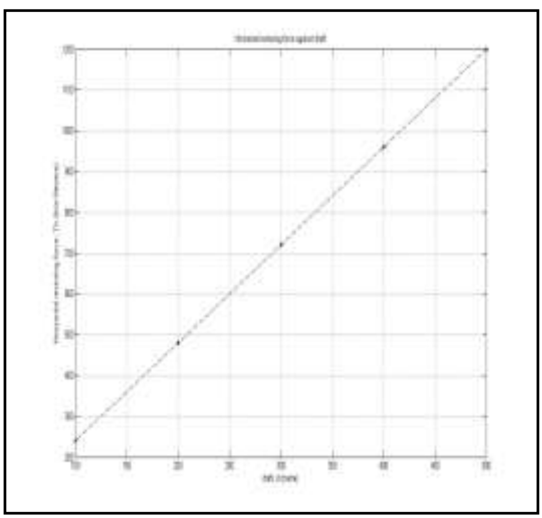


Figure 5: Graph showing horizontal and vertical velocity



The graph above shows the vertical and horizontal change in velocity against the water depth, however if the water depth started increase gradually it will result to increase in the horizontal velocity of the wave particles

Figure 6: Graph showing tension forces against draft of a mooring line



From the result on table (4) and (3) shows that the water particles velocity and acceleration values decrease with increased in water depth. Therefore, any vessel in deeper water will suffer higher velocity an acceleration of water particles compared to that in low water surface therefore vessel in low water depth will experienced higher wave the water particles, velocity and acceleration in low water surface, therefore vessel in low water depth will experienced higher wave. The water particles, velocity and acceleration in low water depth will result to increase in wave frequency, period and wave celerity with respect to the vessel.

Table (5) shows horizontal restoring force applied by the mooring lines system and the suspended line length (draft).

There will be linear increase of the tension force with respect to increase in draft the wave forces acting on a vessel with connected chain to sea bed by mooring line will increase the tension on the chain.

The figure (3), (4), (5), (6) will help to detect the effect of wave forces and tension acting on each mooring line. This project will help to deduce tension, stiffness and provide stability to the vessel in harbour.

**Acknowledgement**

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## 4. Conclusion

The analysis of wave effect on ship and its safety operation in the harbor are mostly ignored due to lack of equipment or may be lack of expertise to carryout designing test or collection of data. This research provides an understanding of the effect of waves acting loads on the ship, the mooring line and how it should be integrated in the analysis of the mooring system. The analysis presented here shows that catenary system is not best suitable for deep waters application, especially in swell waves scenario. Turret mooring system provide an alternative to deep and ultra-deep-water mooring system. The effect of wave acting on a vessel in anchorage and operation at harbor are mostly ignore by the harbor masters. This research provide insight into wave effect on ship at harbor and careful monitoring of the wave formation, the heading angle and the effect on the mooring line is necessary for the stability of the vessel. In extreme waves, cargo offloading, and transfer may be hindered, therefore an operational risk analysis is presented here to understand the effect of wave on ship operation in the harbor.

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# Energy Poverty and the Security Challenges in Northern Nigeria-Incidence and the Potential for Renewables

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***Abstract***- A Multidimensional Energy Poverty Index (MEPI) has been used to study the incidence of energy poverty in Nigeria. Secondary data from the United States Agency for International Development was collated from over 44,000 households, from which calculated MEPI for the various regions of Nigeria show that the southwest had the least incidence of energy poverty, while the northeast region had the highest energy poverty. Cogent connections have been made between recent security challenges in the northeast with energy poverty. Reports taken from studies and the mass media show that vast majority of attacks occur in the geopolitical region. Thus, renewables such as solar and wind energies abundant in northeast Nigeria have been identified as potential solutions to ending energy poverty and hence a strategic pathway to arresting the current security challenges.

**Keywords:** multidimensional energy poverty index, renewable energy, security challenges, North East Nigeria.

## I. Introduction

Energy is an important and key element in human life, influencing virtually all areas such as even environmental sustainability [1]. The World Economic Forum (WEF) describes energy poverty as the "worst poverty of all" and as a major impediment to development [2].

Energy poverty is the lack of access to modern basic energy services such as clean cooking facilities and access to electricity [3]. The need for energy cuts across virtually all areas of human existence for example, access to clean energy would help women in cooking, saving time and energy and avoiding health issues, access to electricity will afford the opportunity to get entertainment from both radio and television, knowledge and information dissemination [4].

Globally, 1.3 billion people do not have access to electricity and over 2.7 billion depend on traditional biomass for cooking consequently making the provision of modern and reliable access on a global scale a huge challenge [3]. Nussbaumer et al. [5] opined that the role of energy cannot be overemphasised in tackling global development challenges such as climate change, education, food security, health, inequality and poverty. Energy poverty is evident mainly in developing countries as majority of the people lack access to various forms of energy [6]. According to Chevalier and Ouedraogo [7], the poor are the main victims of energy poverty and the World Energy outlook [8] reported that sub-Saharan Africa has the highest level of energy poverty with over 31 per cent electrification rate and 80 per cent of the people relying heavily on traditional biomass.

In Nigeria, energy poverty is evident in the frequent interruption of electricity supply to households and industries, households' inability to afford clean energy due to poor income and then households who can afford this pay for it beyond their cost budget. About 40% of the Nigerian populace have no access to electricity grid with over 70% still depending on traditional biomass for cooking [9]. Obi and Menson [10] believe that low access, poor quality and inadequate quantity are the key evidences of energy poverty in Nigeria. Ogwumike and Ozughalu [11] reported that over two-thirds of households in Nigeria rely on fuel wood for cooking hence validating the presence of energy poverty in Nigeria. Some key studies of energy poverty in Nigeria include [9,11, and 12] to mention a few. However, previous approaches on analysing energy poverty in Nigeria have failed to deeply examine and capture the socio-economic deprivations households experience due to energy poverty. This study did not only assess energy poverty at the national level, but also attempt to measure this deprivation at the sub-zone, state, and wealth index level using a Multidimensional Energy Poverty Index (MEPI). Its contribution to the insecurity of life and property currently faced in Nigeria's northeast in the form of terrorism was also be examined. The potential of alleviating energy poverty by harnessing the abundant renewable energy sources available in the region in the form of wind, solar, and biofuels was discussed.

## II. Methodology

### Multidimensional Energy Povervy Index (MEPI)

This methodology was drawn from Nussbaumer *et al.* [5]. The MEPI is a novel metric for measuring energy poverty stemming from literatures from the Oxford Poverty and Human Development Initiative (OPHI) on Multidimensional Poverty Index (MPI) presented in [13, 14]. This is based on Amartya Sen's theory of deprivations and capabilities [15]. The design of the MEPI enables it to capture and evaluate a set of energy deprivations a person or household experiences.

In consideration of the multidimensional nature of energy poverty, the MEPI is basically composed of five dimensions which represent basic household energy service measured by six indicators (see table 1). For a detailed description of the methodology and computation of the MEPI see ref. [5]. Most importantly, the MEPI measures energy poverty in ***d*** variables across a population of ***n*** members. Furthermore, the methodology permits the uneven weighting of the indicators. Energy services perceived by the researcher as more essential where allotted a bigger weighting share (see table 1) the weighting vector *w* is the weight applied to the variable *j*. It is defined as:

$$\sum_{j=1}^{n} w_j = 1 \quad (1)$$

Finally, the MEPI introduces a deprivation cut-off which is the set of conditions a member in the population must achieve. Nussbaumer *et al.*'s study sets the cut-off at 0.3. Therefore, any person whose MEPI is above the 0.3 cut-off is considered as energy poor.

Summarily, if

MEPI > 0.7, Acute energy poverty is incident

0.3≤MEPI≤0.7, Moderate energy poverty

MEPI < 0.3, Low energy poverty

MEPI = H x A

Where **MEPI** = the combination of the information on both the incidence and intensity of energy poverty.

**H = q/n** is the headcount ratio or incidence which represents the proportion of total number considered energy poor; **q** represents the number of people in energy poverty and **n** is the total number of people. **A** is calculated as follows:

$$A = \sum_{i=1}^{n} (k)/q \quad (2)$$

which is the average of the censored weighted deprivation counts $\mathbf{c_i(k)}$. It represents information on the intensity of the MEPI. This methodology stems from the fact that people do not want energy in itself but the services provided by energy, which is made available by different fuels and technologies and has the potential to improve livelihood, health and education as well as reduce poverty in developing countries.

### Data Source

The data used in this research was the survey done by the MEASURE DHS (Demographic Health Surveys) projects. The DHS is funded by the United States Agency for International Development (USAID).

Table 1: The Dimensions and Respective Indicators for the MEPI with Cut-offs, and Weightings in bracket

| Dimension | Indicator (weight) | Variables | Deprivation cut-off (energy poor if….) |
|---|---|---|---|
| Cooking | Modern Cooking fuel (0.2) | Type of cooking fuel | Any fuel use besides electricity, LPG, kerosene, natural gas or biogas |
| | Indoor pollution (0.2) | Food cooked on stove or open fire (no hood/chimney), indoor, if using any fuel beside electricity, LPG, natural gas or biogas | True |
| Lighting | Electricity access (0.2) | Has access to electricity | False |
| Services provided by means of household appliances | Appliance ownership (0.13) | Has a fridge | False |
| Entertainment/education | Entertainment/education appliance ownership (0.13) | Has a radio and/ or television | False |
| Communication | Telecommunication means (0.13) | Has a Mobile phone and/ or Phone land line | False |

The DHS collects and publishes national representative data on issues such as maternal and child health, fertility, family planning, gender, HIV/AIDS, malaria and nutrition. The DHS data was used because the information from the data contains a range of updated indicators related to energy poverty at the household level. The DHS survey on Nigeria for 2003 and 2008 provide estimates for rural and urban areas of the country, the six zones, and several of the 36 states and the Federal Capital Territory (FCT). However, one of the major problems of micro data is likelihood of missing data. This was treated by case deletion to avoid influencing the result of the analysis. For example, in 2008, there were 1333 households with single or multiple missing information this was consequently subtracted from the total number of households interviewed. Also, the 2003 DHS data were collected and used for comparison with the 2008 so as to ascertain the change of energy poverty within 5 years. The 2003 data was chosen because it was the only data with updated information as those from 2008. Although, there were some missing variables in 2003 such as data on generating set, indoor pollution and mobile phones, for the sake of a fair comparison, these data were removed from 2008. Both datasets were representative of the population at that point in time.

**Strengths and Limitation of MEPI**

The MEPI primarily measures deprivation instead of access and takes into account the multidimensionality of energy poverty**.** It further estimates the headcount (incidence) and intensity of energy poverty, i.e., how many people and how energy poor they are**. MEPI** is based on Micro-data (survey) and allows for decomposability between rural and urban and sub-national. It is also more importantly centred on energy services**.** Finally, it is complementary to other metrics such as Energy Development Index (EDI). On the other hand, literature has shown that energy poverty is primarily a challenge in Africa, most especially sub-Saharan Africa where paucity of data is a major obstacle to effective research. This paucity of data poses a major challenge in the computation of the MEPI. However database like the 2008 DHS survey shows an improvement in data evidenced in the addition of more data on energy related services.

Table 2: Interview Data

| Interviewees (Age 15-49) | 2008 | 2003 |
|---|---|---|
| Households | 34,070 | 7,225 |
| Women | 33,385 | 7,620 |
| Men | 15,486 | 2,346 |
| Interview response rate (%) | | |
| Households | 98 | 99 |
| Women | 97 | 95 |
| Men | 93 | 91 |

**III. Results and Discussion**

**Traditional Biomass use and its effect on Households**

This objective was achieved through the review of relevant literatures on the impacts of traditional biomass, and these impacts were categorised into; environmental, health and social impacts. Table 3 presents the findings.

To measure energy poverty, six indicators belonging to five dimensions were considered in order to capture the deprivations households experience from the incapability to use energy services.

Figure 1 shows the percentage of people deprived in each indicator of the MEPI. Also, it compares the performance of the urban and rural areas with that of the national aggregate.

Table 3: Energy Poverty at the National,Urban and Rural Areas

| Category | Impact |
|---|---|
| Environmental | • Reduces Agricultural productivity<br>• Worsens deforestation and desertification<br>• Increases the accumulation of Greenhouse Gas |
| Health | • Indoor pollution from traditional biomass contributes to 1.5 million deaths annually<br>• Toxic fumes from indoor pollution causes more deaths than Malaria<br>• High concentration of CO, NO2, SO2 and TSP leading to chronic illnesses such as lung cancer, pneumonia and allergies<br>• Burns and Scads as well as the possibility of injury and violence during collection |
| Social | • Expands socio-economic inequalities among men and women as women tend to spend more time collecting fuels and cooking<br>• Deprives women and children especially female children the time for formal education |

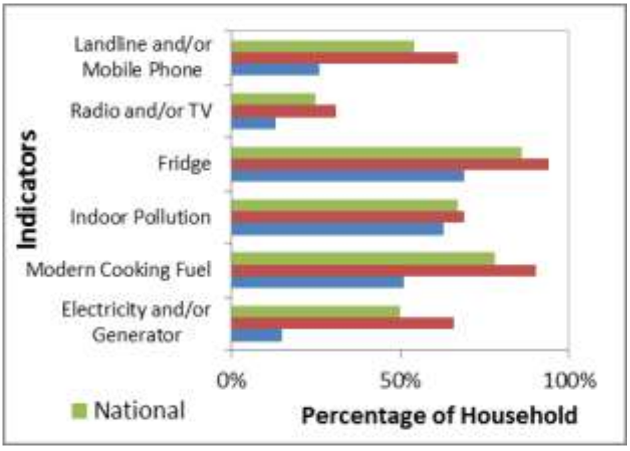


Figure 1: Percentage of Households Deprived in each Indicator for National, Urban and Rural .

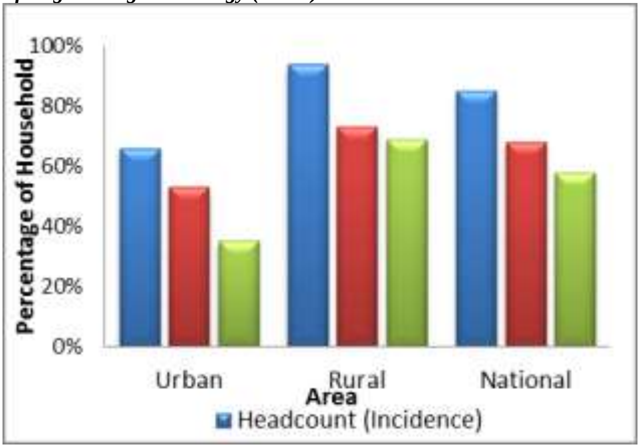


Figure 2: Comparison of Energy Poverty in Rural and Urban Areas with National Aggregate

At the National level, it can be seen that a large proportion of households are deprived in all the indicators except in radio and television.

However, it is important to note that these appliances depend on electricity. The study reports that 78% of households in Nigeria are deprived of modern cooking. The implication of this is that more households depend on traditional biomass other than the clean fuel of electricity, and LPG for cooking and are therefore, exposed to indoor pollution with its associated hazards.

Major reasons for this may be ignorance, affordability and availability of this modern fuel. This tends to be higher in the rural areas where 90% of households are deprived of modern cooking fuel compared to 51% in the urban areas. Drawing from literature, culture and education could be a major determinant for this inequality. Furthermore, it can be seen that 50% of households do not have access to lighting from either grid electricity and/or generators; this implies that they depend on lighting from other sources such as candles and lanterns.

The effect of this deprivation of electricity can also be seen in the percentage of households deprived of cooling from the use of fridges, as can be seen all categories were most deprived in that indicator.

It can be seen from Figure 2 that the incidence of energy poverty is high in Nigeria at 85% which implies that 85% of households in Nigeria are energy poor. In the urban areas, 66% of the households are living in energy poverty. This is relatively higher in the rural areas where 94% of rural inhabitants are energy poor. The intensity of the energy poverty at the national level is 68% which means that an average energy poor household is deprived of 68% of all indicators. Comparing rural and urban households, it can be seen that households in rural areas are deprived of an average of 73% of all indicators. This is lower in urban areas where on the average a household is deprived of 53%. The implication of this is that many households lack these basic necessities more in rural areas than in urban. It furthermore validates studies that rural households are the most affected by energy poverty. It will be recalled that the MEPI cut off was set at 0.3, with a MEPI of 0.58; Nigeria has a moderate level of energy poverty. However, decomposing this to the urban and rural areas, the results show that with a MEPI of 0.35, energy poverty is moderate in urban areas. Energy poverty in rural Nigeria is very acute owing to a MEPI of 0.69 thus; alleviation policies and strategies should first begin in rural areas.

**Energy Poverty at the Geopolitical Zone Level**

It can be seen from the Figure 3, MEPI shows the degree of the energy poverty in each geopolitical-zone in Nigeria. The degree of energy poverty in the South West, South South, and South East is moderate. However, with an exception of the North Central zone, the degree of Energy poverty in Northern Nigeria is critical. This to an extent may reveal the wide gap in development between the South and North. Furthermore, it highlights the capability of the MEPI to be decomposed in order to show the figures for the components of a Nation thereby avoiding erroneous generalisation. To demonstrate this, it can be seen that the MEPI values for the North East far surpasses that of the Nation (Figure 3).

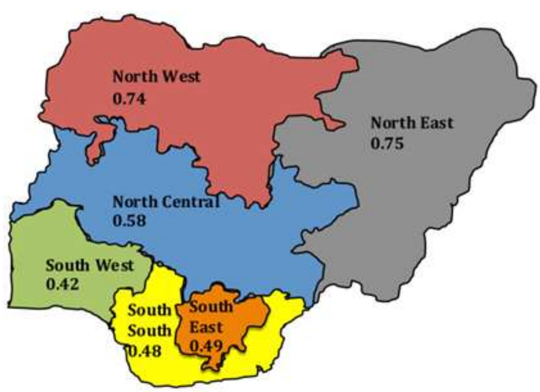


Figure 3: Map showing the MEPI of various Geopolitical zones of Nigeria.

**Relationship between Energy Poverty and Security**

There is a strong correlation between energy poverty and the security challenges currently being faced in the country. Figure 4 shows data collated by Raleigh [16] and reported on the BBC [17] about the incidence of insecurity caused by Boko Haram attacks for the years 2012–January 2015. As the figure shows, the epicentre of these attacks is the northeast of the country and this coincides with the fact that the region has the highest poverty as evidenced by its MEPI of 0.75.

Poverty has been fingered as one of the underlying causes of the conflict, whereby poor, unemployed and vulnerable youths are recruited to the ranks of the militants. As energy poverty is a major aspect of poverty as a whole, tacking energy poverty is a sure route to addressing the conflict and security challenges. Energy poverty not only affects people's access to education and enlightenment through the mass media, it also hinders efforts to combat the security problems. For example lack of steady electricity can mean round the clock CCTV monitoring is not possible. The role renewable energy can play is therefore invaluable.

## Potential of Renewables

As Nigeria's power demand is expected to rise at an average annual increase of 8.2%, it has become evident that frequent disruption of gas supplies to the gas fired generation plants cannot keep up with this demand [18]. This may not augur well if energy poverty is to be overcome. Renewable energy has therefore been identified as an alternative source that can alleviate energy poverty in Nigeria. This is due to its likelihood to solve the nation's huge economic and industrial challenges and its possibility of attracting foreign investors.

In the amended draft Energy Policy Document, data from the Energy commission of Nigeria shows that the average daily solar radiation ranges from 3.5 kWh/$m^2$-day in the coastal belt of the south to 7.0 kWh/$m^2$-day in the North for 4–9 hours daily all year round [19]. This is probably one of the highest in the World. In terms of wind energy, there is also an appreciable amount, and analysis of the patterns suggests an average of 1 – 5 m/s wind speed at 10 m height. Despite the peak months occurring between April and August, there is huge potential to generate between 8 and 51 MWh/yr alone from wind.

As a result, solar and wind energy can potentially lift Nigeria and indeed the country's northeast out of energy poverty if the abundant resources are exploited. Indeed the Draft National Renewable Energy and Energy Efficiency Policy document projected that 30,000 MW can be generated from renewables alone as compared to the total 4,000 MW currently generated from all sources. Therefore, concerted effort and organisation by the government and private sector is required to achieve this goal.

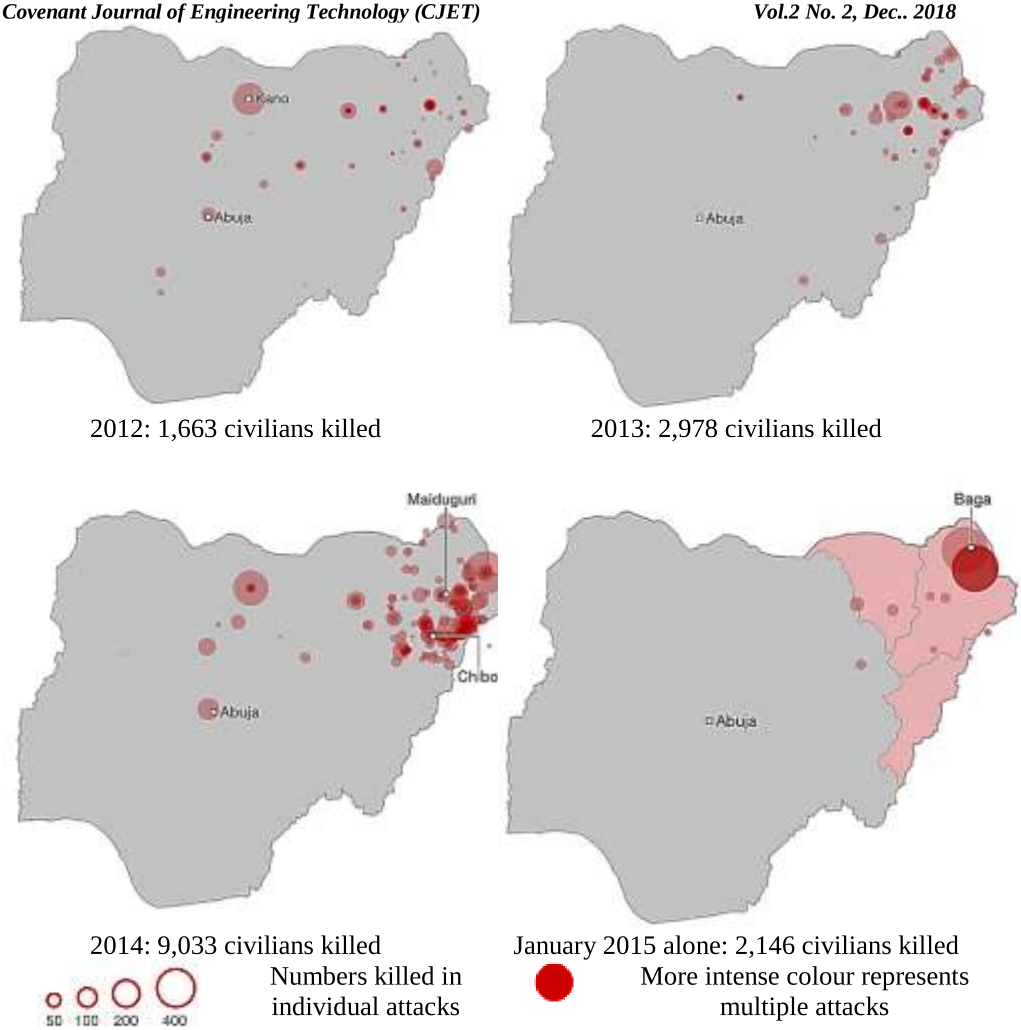


Figure 4: Terrorist attacks in Nigeria 2012-2015 (Source: Source: Raleigh [19]; BBC [20]).

## IV. Conclusions

Developing countries have long been identified to be at the receiving end of energy poverty. Several performance metrics have been used by the WHO, UNDP and other organisations to quantify what the WEF calls "the worse type of poverty". In this study, Multidimensional Energy Poverty Index, MEPI developed by Oxford Poverty and Human Development Initiative (OPHI) on Multidimensional Poverty Index (MPI) was used to study the incidence of energy poverty in the various states and geopolitical regions of Nigeria. The secondary data used was that of the Demographic Health Service of the United States Agency for International Development (USAID) which was obtained by way of interviews collated from over 7,000 and 37,000 respectively for the years 2003 and 2008. Calculated MEPI indices for the various regions of Nigeria show that the southwest had the least incidence of energy poverty while the northeast had the highest. Energy poverty in the northeast region is characterised by deprivation of access to basic modern energy sources such as electricity, petrol, and cooking gas. Energy inefficiency and indoor pollution are predominant. Recent social and security challenges in the northeast of the country have been shown to have a strong correlation with poverty and indeed energy poverty, with the vast majority of attacks occurring in this geopolitical region. As a result, renewables such as solar and wind energies abundant in northeast Nigeria have been identified as having huge potential to ending energy poverty and hence may be alternatives for arresting the current security challenges.

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# Wind Energy Technology in Nigeria: Prospects, Challenges and Solution

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***Abstract***. This paper discusses some of the challenges of wind energy technology, solution and prospects in Nigeria. The major sources of electric power generation in Nigeria are fossil fuel and hydropower. Nigeria is well-endowed with vast resources for conventional energy (crude oil, natural and coal), as well as reasonable amount of renewable energy resources (e.g. hydro, solar, wind and biomass). It is obvious that Nigeria is lagging behind under the wind energy category. Wind power and wind electricity adoption in Nigeria, represents the least developed source of energy. Northern parts of Nigeria experiences wind speeds in the range 6.0 – 8.0 m/s, while parts of Southern Nigeria and mountainous area of the country are in the same range. It is recommended that Nigeria can effectively exploit wind energy technology, if the identified challenges are overcome and the suggested solutions are implemented.
***Keywords***: Wind Power, Nigeria, Wind Energy Technology (WET), Sustainable energy.

## 1. Introduction

Nigeria with an estimated population of above 180 million people, with an ever-increasing demand for energy. The country is located between longitude 80E and latitude 100N, and has two major seasons, wet and dry. The country's economy is largely dependent on oil. Nigeria has one of the lowest net electricity generation per capita rates in the world: 15,000 MW peak load demand to 6,050MW available capacity, resulting in an unreliable power supply and a correspondingly heavy dependence on fossil fuels in industries and residential areas [1]. Major sources of electricity production are fossil fuel, and large- and small-scale hydroelectric generation [3]. While electricity from hydropower plant is widely acknowledged as environmentally friendly, those from fossil fuels and nuclear power have associated environmental limitations [2]. The country depends largely on thermal power plants for the generation of electricity. These are easily fuelled from the country's abundant gas reserves.

A national projection based on 13% Gross Domestic Product growth rate revealed that energy demand will increase from 5746 MW in 2005 to 297900 MW in 2030 while supply should increase from 6440 MW to above 300,000 MW within the same period of years. To accomplish this, requires an additional 11,686 MW every year to meet demand, costing for the period about $US484.62 billion (Ajayi, 2010). Nigeria is endowed with huge resources of conventional energy resources (crude oil, tar sands, natural and coal) as well as reasonable amount of renewable energy resources (e.g. hydro, solar, wind and biomass) [4-5]. The estimate of renewable energy resources in Nigeria are presented in Table 1.

Table 1: Renewable energy resources and estimated reserves in Nigeria *[4]*

| | |
|---|---|
| Hydropower (Large/Small scale) | 14,750 MW |
| Solar radiation | 3.5 - 7.0 KWhm2/day |
| Wind | 2 - 4 m/s at 10m height |
| Biomass | 144million tons/year |
| Wave and tidal energy | 150,000 TJ/year |

Surprisingly, the hydropower reserve data (as shown in Table 1 and supported by other sources (e.g. [5] and [6]) is far less than the long-term target (Table 2) for this resource [4]. The overall targets of renewable energy and total electricity generation are presented in Table 2.

Table 2: Targets for renewable electricity generation (MW) in Nigeria *[6]*

| Resource | Short Term (2008) | Medium Term (2015) | Long Term (2030) |
|---|---|---|---|
| Hydro (large) | 1930 | 5930 | 48000 |
| Hydro (small) | 100 | 743 | 19000 |
| Solar PV | 5 | 120 | 500 |
| Solar Thermal | - | 1 | 5 |
| Biomass | - | 100 | 800 |
| Wind | 1 | 20 | 40 |
| All Renewable | 2,036 | 6,905 | 68,345 |
| All Energy Resources | 15,000 | 30,000 | 190,000 |

From Table 2, it is obvious that Nigeria is lagging behind under the wind energy category. On the other hand, the worldwide total cumulative installed electricity generation capacity from wind power as at the end of 2016 amounted to 486,749 MW, an increase of 12.5% compared to the previous year[7]. It is imperative to know that the amount of the economically extractable power that is available from the wind is said to be more than the current human power use from all sources [8].

However, the African continent though improving in generation capacities, represents the least developed in terms of installed wind power and wind electricity adoption. In sub-Saharan Africa, particularly the West African region, no country has yet generated grid electricity from wind despite the identified opportunities [1]. Table 3 shows the summary of the installed capacity of wind power capacity (MW) in Africa & Middle East as at the end of 2016.

Table 3: Installed Wind Power Capacity (MW) in Africa & Middle East*[7]*

| **Country** | **Installed capacity in 2016 (MW)** |
|---|---|
| South Africa | 1,471 |
| Egypt | 810 |
| Morocco | 787 |
| Ethiopia | 324 |
| Tunisia | 245 |
| Jordan | 119 |
| Others | 150 |
| **Total** | **3,906** |

From Table 3, the 'others' category include countries with small or minimal installed wind power capacity and they are Algeria, Cape Verde, Iran, Israel, Kenya, Libya, Nigeria

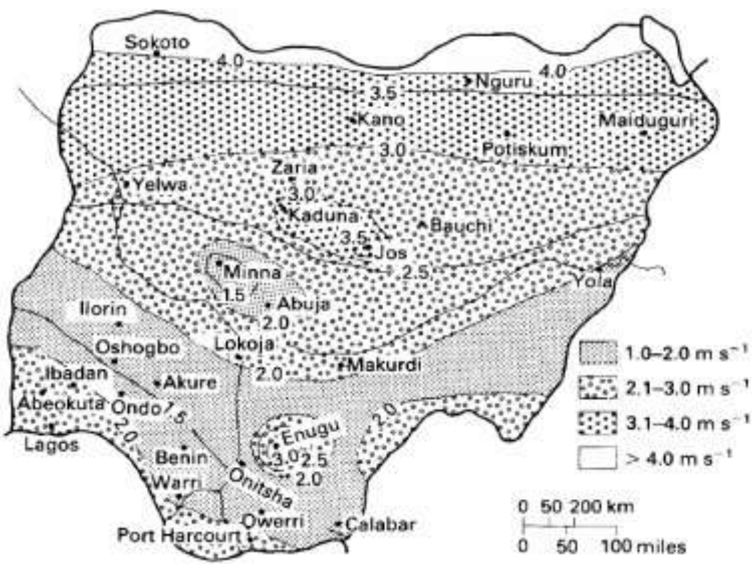
## 2. Wind Power in Nigeria

Individual researchers on their part have made various assessments of potentials and availability based on existing data to determine the magnitude of wind resources in Nigeria. Due to accessibility to wind speed data information, [9] and [10] reported wind speed data in one city while [11] and [10] reported wind speed data across the country [3]. The data collected by these researchers were obtained at different heights ranging from about 5 m to 15 m, but a mean average height of 10 m was agreed upon as the focal height [17-18].

The map (Fig. 1) shows the suitable use of wind power in each state, based on wind at 10 m elevation.

From the map, it was deduced that Northern Nigeria experiences wind speeds in the range 6.0 – 8.0 m/s whereas parts of Southern Nigeria and mountainous centers are in the same range. It was also noted that twelve states experience wind speeds between 2.5 m/s and 4.0 m/s thereby making it possible for borehole water pumping use. Fifteen states experience wind between 4 m/s and above, hence enabling wind generated electricity in those states. Also, ten states experience wind above 6 m/s giving them a very good potential for wind generated electricity. Further analysis of these wind resources revealed that the North, Central and South-East of the nation possess enormous potential for harvesting wind energy, with possible wind speeds reaching as high as 8.70 m/s in the north [12].

Figure 1: Nigeria Wind regime [13]




However, Fadare (2010) make use of artificial neural networks to predict the wind speeds distribution across Nigeria and compared the predicted wind speeds with measurements data from 28 stations that span between 1983 and 2003. He predicted monthly average wind speed ranging from a minimum of 0.8 m/s for Ondo (in south region) to maximum value of about 13.1 m/s for Kano (in north region) with both values occurred in December. The overall average annual wind speed of 4.7 m/s was predicted for Nigeria. The measured data presented in the study indicated that maximum average annual wind speed of 9.47 m/s was recorded in Jos (closely followed by 9.39 m/s in Kano) while minimum value of 1.77 m/s was recorded in Ondo [3]. Recorded samples of the monthly isovents for selected months using the predicted values are represented in the figure 2.

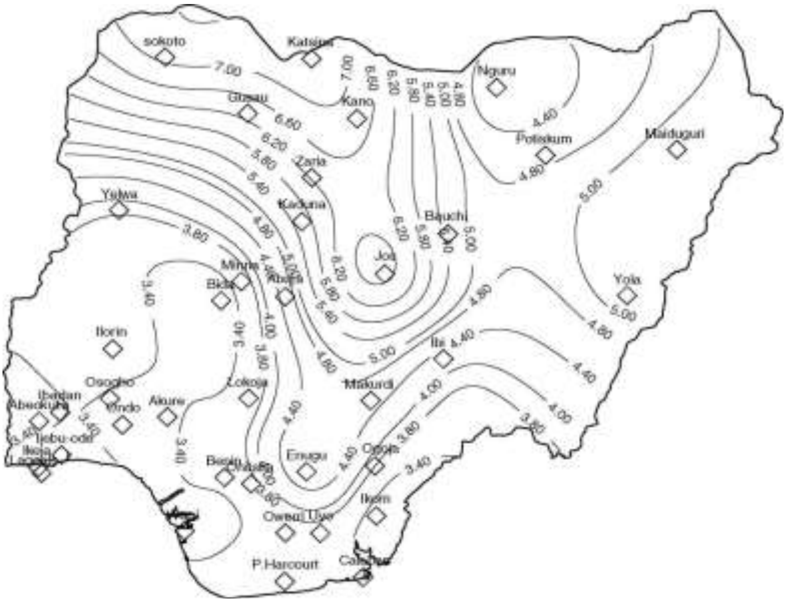



Figure 2: Predicted monthly average wind speeds (m/s) distribution (isovents at 10 m height) in Nigeria for the month of June [14].

## 3. Wind Energy Technology Challenges and its Corresponding Tackling Measures

### 3.1. Challenges

There are various challenges affecting the development of wind energy technology (WET) in Nigeria. Some of these problems are identified by [6] [15] as:

- reluctance of government and its agencies to encourage wind energy technologies,
- low government financial support and non-availability of fiscal incentives,
- lack of awareness,
- inadequate institutional framework and resource assessment, and
- technical ineptitude and limitation.

### 3.2. Tackling Measures

**a) Development of a Robust Wind Energy Technology Policy**

Investors need healthy government policy that will create a favorable environment for profitability. Incentives can be put in place such as sales tax, concessional import duties, and excise duty relief to encourage and attract investors in WET. The reassurance from the government for a viable market in WET is necessary. And this can only be expressed via policy making. This will serve as an index to rate the level of readiness the government has in supporting and promoting WET in Nigeria.

**b) Research and Development**

Advancement in WET can be achieved when there are established institutions, whose focus is to harness all aspects of WET, working round the clock in finding out how to increase the contribution of WET to the energy mix of the country, while laying emphasis on rural electrification as well. Having such a team on ground will ensure the growth of WET and will create a sustainable system and accountability in WET in the country.

**c) Adequate funding of WET**

Interventions from government, investors, and other sources can be pulled together to setup sustainable funding for the advancement of WET projects in Nigeria. The government's serious involvement in WET will spur adequate funding as it will be easier to earn the trust of local and foreign collaborators. A special funding agency could also be setup that will solely bear the responsibility of sourcing for funds for WET.

**d) Working plan & Road map**

The Renewable Energy Master Plan will be a vital resource if there can be serious devotion to the suggestions contained therein. Part of this suggestion includes the suspension of the Renewable Energy (RE) import duties, integration of RE into non-energy sector policies, establishment of national RE development agency, standardization of RE products and establishment of RE fund to provide incentives, micro-credits schemes, training and also funding R & D [2].

## 4. Conclusion

Nigeria has an enormous amount of wind energy resource that has not yet been tapped. Inland and onshore possibilities are vast for the growth of WET in the country. The government cannot afford to neglect this important aspect of energy, therefore deliberate steps must be taken to harness, preserve and sustain WET in Nigeria. This task is not a one-man affair; thus, the government must be willing to partner with countries that have vast and advanced knowledge in the technology. This will save time and set Nigeria on track with other countries developing WET around the globe. The determined pursuit and establishment of WET in Nigeria is important to the growth of the energy sector. It will reduce the fossil fuel consumption thereby preserving the environment and saving the planet at large. It will also aid in the realization of the country's vision of becoming one of the 20 largest economy in the world (vision 2020).

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An Open Access Journal Available Online

# Finite Element Analysis of Concrete Gravity Based Platform Subjected to Sudden Crash (Impact) Load Using ANSYS

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***Abstract***: The design, analysis and construction of offshore structures as well as their modeling are one of the most demanding sets of tasks faced by engineering profession due to the complexity of structural designs and the large volume of elements used in the model. Finite element analysis (FEA) technology has become a very important tool for evaluating the structural integrity of massive and gigantic structures of which offshore platforms is an example. Offshore structures when installed are constantly faced with different forces/loads ranging from environmental to accidental loads and the later was the impacting load under consideration. This paper carefully illustrates the design and analysis approaches and requirements for a reinforced concrete based gravity platform, a fixed type of offshore structure which was subjected to a crash load and simulated with a computer based finite element analysis tool-ANSYS EXPLICIT DYNAMICS. The scenario was a collision between an offshore transporting vessel and the said fixed platform. Impacting velocities of 5m/s,10m/s, 16m/s, 50m/s and 100m/s were used and results obtained for deformations and stress induced. The study was done to see at what velocity the structure compromise its load bearing capacity and it was observed that the deformation was proportional to velocities increase.

***Key Words***: Finite Element Analysis (FEA), Gravity Based Structure (GBS), Collision, ANYSY Simulation, Accidental load.

## 1. Introduction

As the demand for oil and gas is continually on the increase globally, exploration and production has moved ever more into the offshore environment which has led to the installations of numerous oil and gas platforms for drilling and production operations. Some of these platforms are fixed or floating. The **Fixed** as the name implies is permanently placed in position throughout the offshore operations, while the **Floating** structure floats on the surface of the sea by some devices. These structures are constantly been faced with external forces [1].

The Floating structure has topsides located on a floating hull system which floats with the help of either a *pontoon* (a flotation device with buoyancy that can float itself as well as a heavy load) or a mooring system to hold on station. The pontoon and the mooring systems help the floating platform achieve stability. Examples of such structures are Submersible, Semi-submersible, drill ship, FPSO, Tension leg platforms [2].

The Fixed types has their topside structures attached to the seafloor via a jacket, piles or a reinforced concrete legs and they are categorized into Jacket, Jack Up, Tower, Compliant tower, Gravity Structure. The latter type of *fixed* structure was the focus of this research [2].

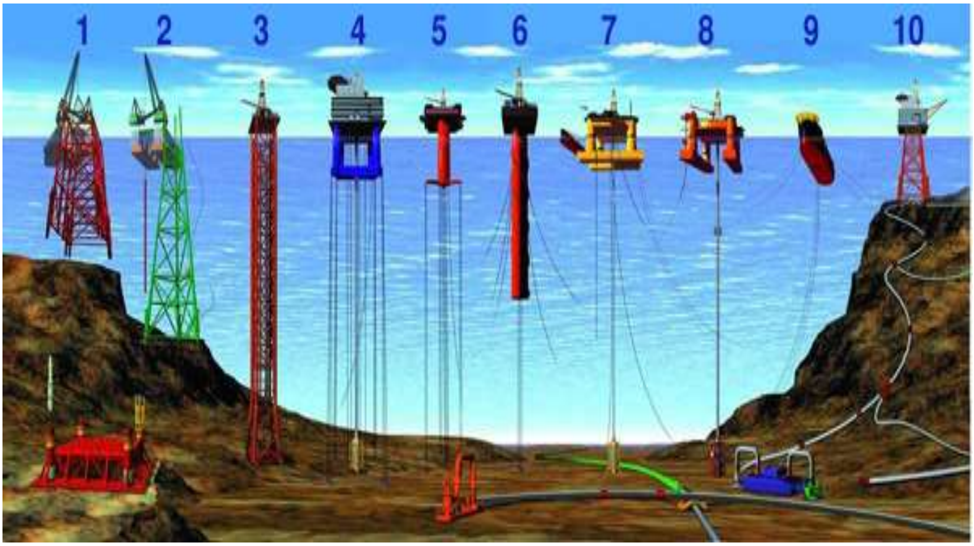


Fig. 1 Types of Offshore Oil and Gas Structures

**1 & 2** Conventional fixed platforms (deepest: Shell's Bullwinkle in 1991 at 412 m/1,353 ft)

**3** Compliant tower (deepest: ChevronTexaco's Petronius in 1998 at 534 m /1,754 ft)

**4 & 5** Vertically moored tension leg and mini-tension leg platform (deepest: ConocoPhillips' Magnolia in 2004 1,425 m/4,674 ft)

**6** Spar (deepest: Dominion's Devils Tower in 2004, 1,710 m/5,610 ft)

**7 & 8** Semi-submersibles (deepest: Shell's NaKika in 2003, 1920 m/6,300 ft)

**9** Floating production, storage, and offloading facility (deepest: 2005, 1,345m/4,429 ft Brazil)

**10** Sub-sea completion and tie-back to host facility (deepest: Shell's Coulomb tie to NaKika 2004, 2,307 m/ 7,570 ft)

### 1.1 Loads on Offshore Structures

Offshore structures are constantly faced with various forces/loads which are categorized into [3]:

- ***Static loads***

- Dead weight (weights of the platform and any permanent equipment and appurtenant structures which do not change with the mode of operation. i.e the structural weight in air, equipment permanently installed on the platform. Example weights of pile, ballast, etc).
- Hydrostatic forces (forces acting on the structure below the waterline including external pressure and buoyancy).

- ***Dynamic Loads***

- **Operational loads** or **Live loads** (loads imposed on the platform during use and which may change either during a mode of operation or from one mode of operation to another.eg the weight of drilling and production equipment which can be added or removed from the platform, the weight of living quarters, heliport etc).
- **Environmental loads** (loads imposed on the platform by natural phenomena including: wave, current, wind, earthquake, snow, ice and earth movement. Environmental loads also include the variation in hydrostatic pressure and buoyancy on members caused by changes in the water level due to waves and tides).
- **Construction loads** (loads arising from fabrication and installation of the platform and components)
- **Accidental loads** (the impact of platform collision with vessel, helicopter crash, objects drop, fire etc)

### 1.2 Concrete Gravity Base Structure (CGBS)

The term Gravity Based Structures (GBS) implies two main characteristics; firstly, the foundation is not piled but of gravity type and secondly, the main structural elements are of concrete reinforcement. They are fixed structures that are held in place against environmental action solely by their weight (gravity) and that of ballast contained [1].

The Concrete offshore structures are used in the oil and gas industry for drilling, extraction or storage units for crude oil or natural gas in extreme offshore environments were the wave frequency is of high magnitude like the Norwegian North Sea. These structures are massive and house machineries and equipment needed to drill and/or extract oil and gas. Other concrete structures which are not applicable within the oil and gas industry like the wind turbines have being in operation [4].

The early development of gravity platforms was in the 1970s in the North Sea. This was driven by the generic requirement to store large volumes of oil and support heavy topsides in deep waters. The discovery/ development of this structure solved the problem of pipeline infrastructural transportation of crude oil to land which was immature then [5].

Fig. 2 Gravity Based Concrete Structure

*CGBS Design Considerations.* The design, analysis and construction of offshore structures are one of the most demanding sets of tasks faced by engineering profession.

Three design steps are required in offshore structure design [3] -

- **Foundation Design**

For the fixed structures for example the concrete and jacket platforms, the design consideration is dependent on the weight of the structure, the environmental loads and the soil characteristics. The base for a CGBS or the pile for a jacket should be design to withstand these loads. The choice of location for installation is based on geotechnical report gotten and the soil laboratory test.

- **Naval Architecture Design**

This addresses two issues in the design of offshore structures, the hydrostatics and hydrodynamics requirements. The hydrostatics is the ability of the structure at rest to be afloat. And the hydrodynamics requirement is the resistance the structure has towards the motion due to water flow. It also examines the static stability of the structure, which is its ability to restore itself to the original upright position after being hit/ inclined by wind, wave or other loading conditions.

- **Structural Design**

For validation of the design, structural analysis is conducted. The results gotten from the validation is used for the selection of construction materials.

Structural design validation includes: a *strength check*- to ensure sufficient resistance for material yield strength for all components, a *stability check*- for buckling (propagation of failure on the structure) resistance for all structural components subjected to compression, and a *joint check*- this ensures sufficient connecting capacities between various components. In addition, advanced design validation/ authentications may be required for accidental loads, fatigue and corrosion [6].

Some recommended codes and standards for offshore designs include BS 6235 (1982), API RP 2A-WSD (2000), and DNV-OS-C101 (2011) for steel structures and DNV-OS-C502 (2010) for concrete platforms

*Impact Load.* Impact load is an accidental load and it's dynamic in nature (i.e. it varies with time). A typical example is the scenario of this work. During this collision, the striking vessel converts its kinetic energy wholly or partially into strain energy in both objects depending on the magnitude of the velocity of impact. Various analysis tools have been developed to analyze the aftermath of this collision (deformation, damage stress etc) like ANSYS finite element analysis tool which was used for this simulation.

## 2. Methodology

The accidental impact from an offshore transporting vessel to a gravity based platform having a rectangular-based concrete reinforced caisson with a measurement of 126m x 94m x 16m was simulated using ANSYS EXPLICIT DYNAMICS. The structure has four hexagonal shaped shafts each of length 60m, diameter 18m and thickness of 8m, mounted at seabed of water depth 45m. The shafts extend 15m above the water level to provide support for the topside deck. The total weight of the CGS (assumed) is 42,500,000 kg (42,500 tons) with the concrete reinforcement inclusive. The colliding vessel is made of structural steel, with a deadweight/total weight of 4,070 ton (4,070,000kg).

The ANYSY is a general-purpose finite-element analysis/modeling tool for solving numerically problems in the field of sciences and engineering. These problems include but not limited to static/dynamic, structural analysis (both linear and nonlinear), heat transfer, fluid, as well as acoustic and electromagnetic problems [11].

Finite Element Analysis FEA, is a simulation method most often use to predict the physical behavior of structures/systems. In other words, it gives a clue of how a product reacts to real-world forces, vibration, heat, fluid flow and other physical effects. FEM working method is by breaking down (discretizing) a real object into a large number (thousand) of finite elements with nodes, such as little cubes. Mathematical equations then help in predicting the behavior of these elements at those nodes [9, 10].

The geometry model of the structures were done using SolidWorks CAD tool. This tool enables designers to mathematically create solid models of objects that can be stored in a database. It has the advantage of converting 2D drawings immediately to 3D once as desired.

Rock mounts were placed on the seabed to prepare the foundation for CGS installation to accommodate unevenness of the seabed, also mounted at the base edges of the caisson after installation of the CGS for scour protection.

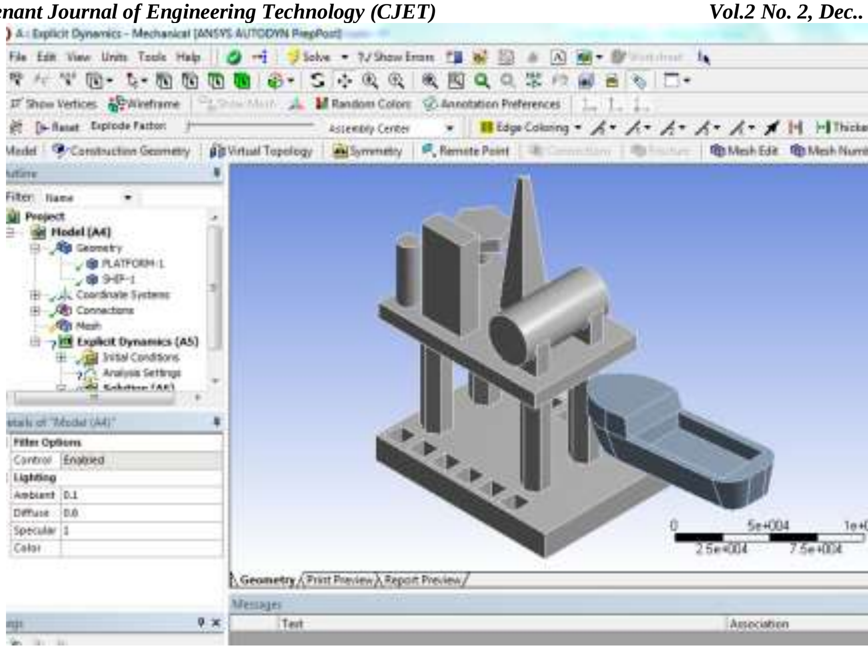



Fig. 3 Imported geometry to ANSYS environment

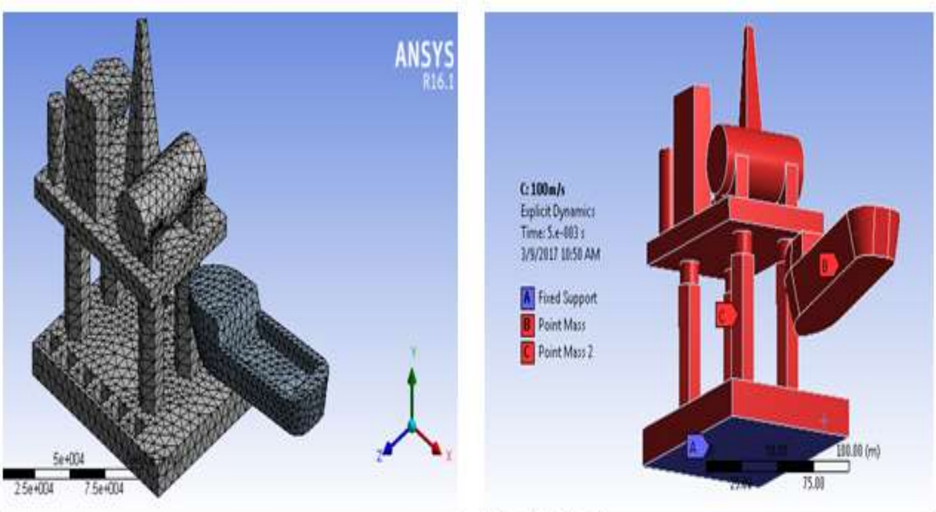



Fig. 4 Meshed Model and model showing fixed support

## 2.1 Material Data

Table 1 Concrete Structure Constants

| | |
|---|---|
| Density | 2400 kg/m$^3$ |
| Coefficient of Thermal Expansion | 5 C$^{-1}$ |
| Ultimate Strength | 4.8e8Pa |
| Concrete Material Grade | CONC-35MPA |

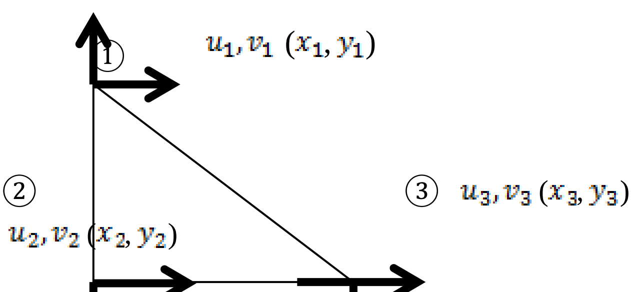
## 2.2 Assumptions Made

- The modeling of structures is simplified but has the same quality and the dimension.
- The bottom of the platform is treated as rigid (fixed).
- The structure is located at a shallow water of about 45m, hence the effect of wave and sea frequency are neglected.
- The collision is considered at 90 degree.
- The investigation were for a collision of 5m/s, 10m/s 16m/s, 50m/s, and 100m/s vessel velocities.
- End time of 0.005s.

## 2.3 Governing Equation

The finite element governing equation for displacement and stress of this vessel-platform impact problem scenario is derived from the principle of virtual work, *which states that the external applied load (**F**) subject on a structure must be in equilibrium with the internal stress (displacement)* [7].
Mathematically,

$$\mathbf{F}=\int_{\Omega}[\mathbf{B}]^{T}\boldsymbol{\sigma}\, d\Omega \qquad (1)$$




$$U(x,y)=H_1(x,y)U_1+H_2(x,y)U_2+H_3(x,y)U_3$$
$$V(x,y)=H_1(x,y)v_1+H_2(x,y)v_2+H_3(x,y)v_3$$

$$\begin{Bmatrix} u \\ v \end{Bmatrix}=\begin{bmatrix} H_1 & 0 & H_2 & 0 & H_3 & 0 \\ 0 & H_1 & 0 & H_2 & 0 & H_3 \end{bmatrix}\begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \end{Bmatrix}=[N]\{d\} \qquad (2)$$

$$\{\sigma\} = [D]\{\varepsilon\} \tag{3}$$

$$[\varepsilon] = \begin{pmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{pmatrix} \tag{4}$$

$$\begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = \begin{bmatrix} \frac{\partial H_1}{\partial x} & 0 & \frac{\partial H_2}{\partial x} & 0 & \frac{\partial H_3}{\partial x} & 0 \\ 0 & \frac{\partial H_1}{\partial y} & 0 & \frac{\partial H_2}{\partial y} & 0 & \frac{\partial H_3}{\partial y} \\ \frac{\partial H_1}{\partial y} & \frac{\partial H_1}{\partial x} & \frac{\partial H_2}{\partial y} & \frac{\partial H_2}{\partial x} & \frac{\partial H_3}{\partial y} & \frac{\partial H_3}{\partial x} \end{bmatrix} \{d\}$$

$$\{\varepsilon\} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = [B]\{d\} \tag{5}$$

$[B]=$

$$\frac{1}{2A}\begin{bmatrix} (y_2 - y_3) & 0 & (y_3 - y_1) & 0 & (y_1 - y_2) & 0 \\ 0 & (x_3 - x_2) & 0 & (x_1 - x_3) & 0 & (x_2 - x_1) \\ (x_3 - x_2) & (y_2 - y_3) & (x_1 - x_3) & (y_3 - y_1) & (x_2 - x_1) & (y_1 - y_2) \end{bmatrix}$$

$$H_1 = 1/2A\begin{vmatrix} (x_2y_3 - x_3y_2) \\ +(y_2 - y_3)x \\ +(x_3 - x_2)y \end{vmatrix}, \quad H_2 = 1/2A\begin{vmatrix} (x_3y_1 - x_1y_3) \\ +(y_3 - y_1)x \\ +(x_1 - x_3)y \end{vmatrix}, \quad H_3 = 1/2A\begin{vmatrix} (x_1y_2 - x_2y_1) \\ +(y_1 - y_2)x \\ +(x_2 - x_1)y \end{vmatrix}$$

From equations (3) & (5) we have;

$$\mathbf{F} = \int_{\Omega} [\mathbf{B}]^T [\mathbf{D}] [\mathbf{B}] \, d\Omega \, [\mathbf{d}] \tag{6}$$

The element stiffness matrix for the impacting force is expressed as;

$$[\mathbf{F}] = [\mathbf{K}] [\mathbf{d}] \tag{7}$$

Integrating (6) yields;

$$[\mathbf{F}] = \mathbf{t}[\mathbf{B}]^T [\mathbf{D}] [\mathbf{B}]\mathbf{A} \tag{8}$$

Equating (6) and (7),

$$[\mathbf{K}] = \mathbf{t}[\mathbf{B}]^T [\mathbf{D}] [\mathbf{B}]\mathbf{A} \tag{9}$$

Where:

**[F]** = Impacting force, **[K]**= Stiffness matrix, **[d]**= Displacement/Deformation, $\varepsilon$ = Strain, **σ**=Stress, A=Area**,** **t**=Plat thickness, H= Shape function.

[8, 11]

## 3. Results and Discussion

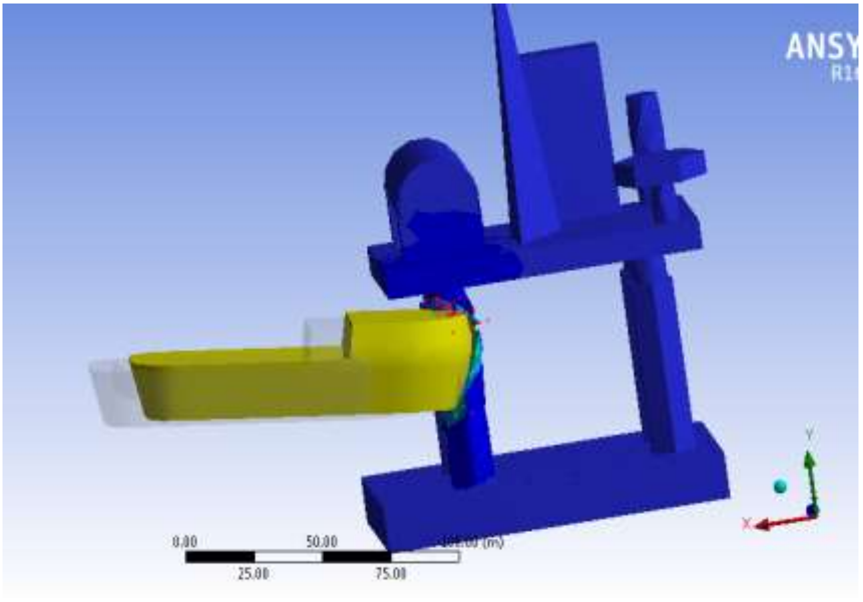



Fig. 5 Simulation model of the collision

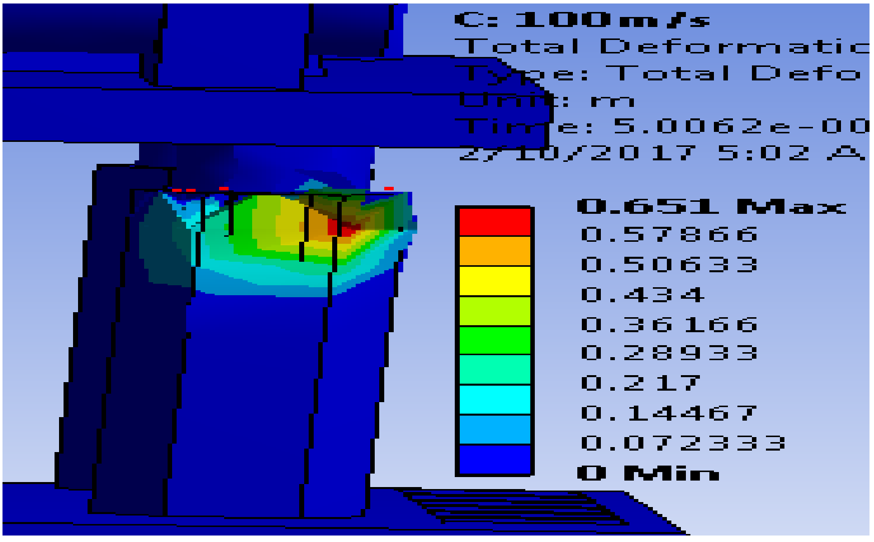



Fig. 6 Deformation contour plot

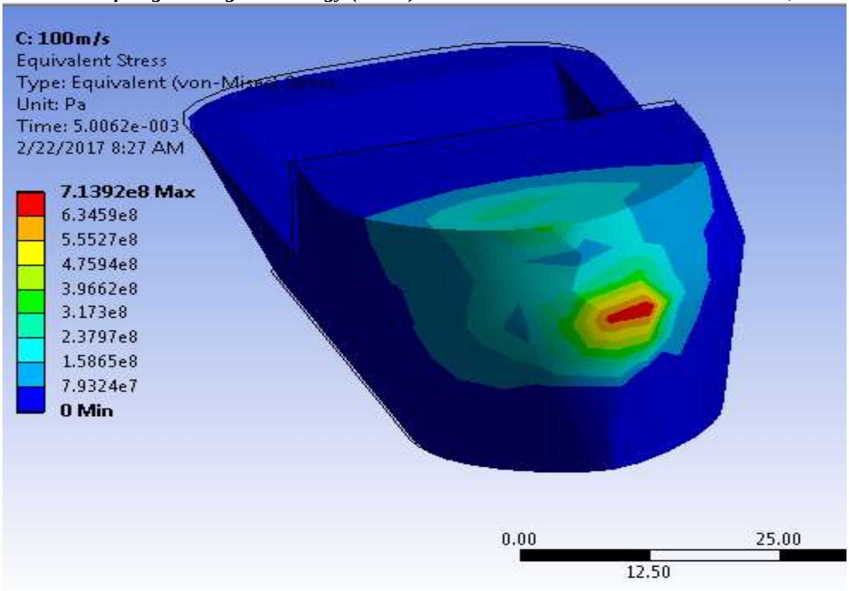



Fig. 7 Stress contour plot

Table 2 Plot of Velocity against Total Deformation

| Velocity (m/s) | Total Deformation (m) | Damage Value | Maximum Occurred |
|---|---|---|---|
| 5 | 0.02503100 | 0.00000 | Ship |
| 10 | 0.05019100 | 0.05952 | Ship |
| 16 | 0.08067100 | 0.18284 | Ship |
| 50 | 0.21491000 | 0.83078 | Platform |
| 100 | 0.65100000 | 1.00000 | Platform |

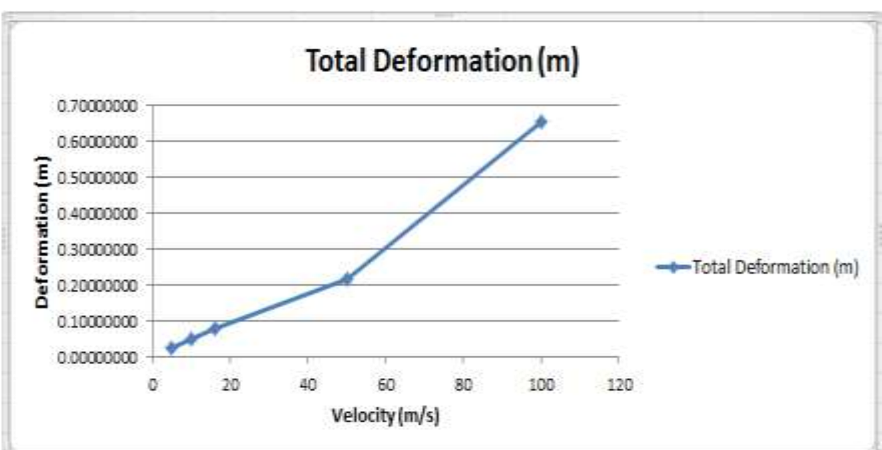



Fig. 8 Graph of total deformation Versus Velocity

Table 3 Plot of Velocity against Stress

| Velocity (m/s) | Stress(e7)Pa | Maximum Occurred |
|---|---|---|
| **5** | 0.0000000 | |
| **10** | 7.2299 | Ship |
| **16** | 11.695 | Ship |
| **50** | 19.615 | Ship |
| **100** | 71.392 | Ship |

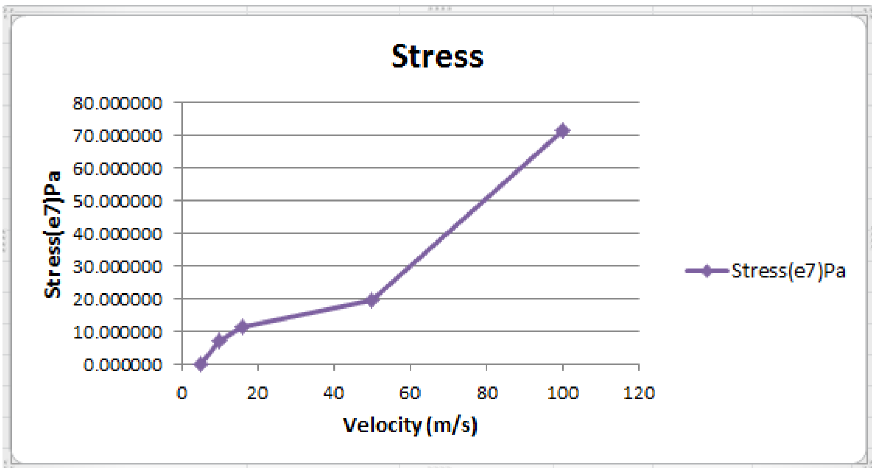



Fig. 9 Graph of Stress versus Velocity

In FEA/ANSYS EXPLICIT DYNAMICS, the contour plot is interpreted using the contour scale which has different colour codes [12]. Simulations were done for the chosen velocities and results gotten for deformation/displacement and stress on both platform and vessel. Damage simulations were carried out also.
Damage in ANSYS simulation shows the load bearing capacity of a structure under consideration. If damage value of 1 is gotten after simulation means the structure has failed [13].

**Deformation and Damage**

Table 2 and Fig. 8 show results of the total displacement and damage at various velocities. The results revealed that the deformation is proportional to increase in velocity. It also shown that at velocity 50m/s, the platform started compromising its load bearing strength and totally collapsed at velocity 100m/s. From the table it can be seen that the maximum occurred deformation for 50m/s and 100m/s is on the platform depicting that at short impact time of 0.005s the energy generated was transferred to the platform.

**Stress**

Table 3 is the tabulated results for stresses at the various velocities. This result revealed that the 100m/s velocity exerted a maximum internal force of 7.1392e8Pa, which exceeded the ultimate strength of material in table 1 when compared. This implies that, failure has occurred. The induced stress occurred more on the ship showing that energy was conserved on the impacting structure, see table 3.

## 4. Conclusion

The study looked into the deformation/ damage rate and stress at the various velocities. And also compared stresses with the material yield strength (the point at which the material starts experiencing deformation) of the structures. It was concluded that:

1. The deformation, stress increases as the velocity increases.
2. At velocity of 50m/s and above the structures started compromising there load bearing capacity.
3. The 100m/s velocity which is equivalent to a velocity of RPG (Rocket Propelled Grenade), both structures experienced high stresses which are greater than their material yield strengths.

It is worthy of note that accident in general does not ring a bell nor been sent by the voodoos but caused as a result of human errors. In order to reduce the rate of accident offshore we therefore recommend that a system like INFRARED MOTION SENSOR OR INDECATOR that will alert and re-awaken the consciousness of the personnel onboard the ship and those on the platform about the presence of an oil facility or an oncoming transporting vessel respectively from a distance.

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# Modeling and Analysis of Fouling Behaviour in Plate and Frame Heat Exchanger

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***Abstract*–** The fouling of heat exchangers in the oil and gas industry is not only a recurring challenge in refineries but it is also becoming a challenge in crude oil production and treatment facilities where heat exchangers are deployed to cool the crude oil temperature downstream of stabilization system prior to storage. A predictive mitigation approach to addressing fouling in heat exchangers remains the most viable option to avoid production train capacity limitations, unplanned shutdown and attendant loss of revenue. Considerable researches have been carried out which lead to the development of models used for predicting fouling resistances in shell and tube heat exchangers. However, this study focused on evaluation of the performance of a plate and frame heat exchanger utilized in cooling of crude oil prior to storage in a cargo tank for export. It also developed a fouling resistance suitable for forecasting the exchanger performance and predicting the maintenance management scheme. The data employed were continuously measured for three years and employed for the analysis. It found that the lower the hot stream approach temperature, the more the fouling resistance. In addition, the work validates that as the fouling resistance increases with time, the efficiency of the plate and frame heat exchanger diminishes.

***Keywords***: Fouling Models, Fouling Resistance, Energy System, Heat Exchanger, Scaling

## I. Introduction

Heat exchangers are important process equipment utilized in nearly all industries and play key role in the quest for optimal use of energy. They are often deployed to recover heat energy, which otherwise would be wasted. The applications of heat exchanger are significant in various sectors such as power generation, aviation, space heating, refrigeration and air-conditioning systems, chemical process facilities, sewage treatment systems, refineries, cooling and heating.

In the upstream sector of the oil and gas industry, heat exchangers are deployed in oil processing system, gas compression systems and in many utility systems. However, the heat exchangers are frequently restricted by the process-related depositions on the heat transfer surfaces, which often lead to higher operation costs, higher maintenance costs, safety hazards, environmental hazards, throughput limitation and inefficient energy recovery [1]. This deposit known as fouling is one of the biggest challenges facing the efficiency of a heat exchanger. Fouling involves the deposition of material on to a process surface [2]. [3] described fouling as a process where the surfaces separating the fluids in the heat exchanger accumulate deposits as the fluids flow through them. It is the undesirable accumulation of matter on a heat transfer surface resulting in reduced thermal efficiency and increased pressure drop [4]. Fouling rate, also defined as the difference between the material deposition and removal rates on the heat transfer surfaces [5], is an important phenomenon that has capacity to determine the performance of a heat exchanger. Loss of revenue attributed to heat exchanger fouling can be significant. Inadequate heat exchanger performance costs some international oil and gas companies approximately seven hundred and fifty million US dollars ($750 million) per year due to lost throughput and increased fuel and utility consumption, and concurrently exacerbates the environmental footprint [4]. The cost of fouling is connected to energy wastage and associated downtime. Heat exchangers for use in preheat trains of crude oil refineries currently appear to be designed based on pre-specified fouling factors [6]. Fouling has a chronic operational effect that is considered the major unsolved problem in heat transfer technology [7].

## Fouling Formation

Like other phenomena, several factors are responsible for fouling formation on a heat transfer surface. [8] performed a study on the fouling features of Crude Oil from Australia and found that surface temperature has a significant effect on fouling rates. An increase of approximately 80oC results in triplicating of the initial fouling rate. [9] posited that in some crude oils, an increase in bulk temperature does not always result in increase in initial fouling rates. The study further proposed a threshold fouling model using the film temperature in the Arrhenius expression after conducting experiments in a high pressure, high temperature recirculation flow pilot-scale fouling test rig with different crude oils at certain operating conditions. The model's accuracy was shown to predict initial fouling rates very close to experimental data. In a combined experimental and modeling study to relate crude oil properties to their intrinsic fouling propensities, [10] observed that the effluent temperatures of crude oil continuously declined due to buildup of thermal insulating foulant on the wall. The study developed a theory that fouling is driven by coking reaction and mass transfer; and mostly influenced by oil's solvency power and the contents of asphaltene, basic nitrogen, and metals which were combined into a fouling propensity index used for developing improved fouling reduction methods. In a related study involving the mixing of crude oil before loading into the test apparatus, [11] observed that different mixing methods can produce different heat transfer coefficients and different fouling rates. [12] expounded a simple, fundamental theory that certain velocity and shear stress thresholds in horizontal flows can be responsible for sedimentation particulate fouling and the values compare favorably with industrial experience. [13] simulated a crude oil fouling process using asphaltene precipitation to study the aging process of the fouling layer and observed that wall shear stress has a high impact on mitigation of fouling as it enables the removal of fouling precursors and thus reduce the deposit formation. Various studies suggest that fouling formation is caused or accelerated by several factors such as wall/bulk temperatures, flow velocities, aging, shear stress and fluid properties.

**Modeling of Fouling Behaviour**

The threshold fouling approach has become an accepted tool for analyzing fouling data but there has been little activity in the development of quantitative models for the past ten years [14]. [15] studied fluid dynamics and phase behavior of crude-oil fouling in a closed-end heat-exchanger on the basis that the deposition process associated with fouling was due to asphaltene precipitation and a two-step chemical reaction. It predicted phase equilibrium constants used to quantify the asphaltene precipitation rate. The outcome showed that the delicate interplay between heat transfer and fluid dynamics, which accompanies the flow, leads to enhancement and suppression of chemical reaction and precipitation-driven fouling, and an overall rise in the fouling rate. [15] modelled and simulated different crude oil deposit aging scenarios in a crude oil refinery preheat train wherein the transients of fouling and aging as well as the interactions between individual units were captured. Based on this, the deleterious impact of fouling and concomitant aging, quantified in terms of thermal resistances, was significantly reduced by fast aging as opposed to medial, slow, or no aging of the gel deposit. Faster aging rate reflected improved heat recovery and a lesser demand for and lower cost of heat exchanger cleaning. The concomitant higher growth of coke deposit due to aging, however, resulted in greater hydraulic resistance, which is inimical to operations.

Moreover, [16] stated that crude oil fouling researches should be directed to reflect the fouling behaviour of operating exchangers. Based on this, some studies have been carried out to develop models for predicting fouling rate or fouling initiation time. However, despite the existence of the studies, there has not been any that has developed a model that can be used to generalize or universally analyse fouling behaviour in different kinds of heat exchanger. The models are exchanger specific. In addition, several of the previous studies were done with different fluids (other than crude oil) which have different characteristics. Further to this, most of the existing research endeavors were focused on shell and tube heat exchangers in small laboratory scale test sections such as heated rods and short tubular sections. This does not represent dynamic operating conditions as would be observed on a life process plant. More so, in the studies where crude oil was used, most of them were based on stabilized crude used in the downstream process plants (refineries) and not on that used in the upstream. Thus this study focused on evaluation of the performance of a plate and frame heat exchanger deployed in the oil & gas production/treatment facility of upstream sector with operational data. It also focused on in situ experimental measurement of crude oil flow data in a crude cooler facility belonging to a leading oil and gas firm in Nigeria. The data employed were continuously measured for three years and employed for the analysis. The work led to the development of an empirical model that can predict future fouling potential, hence providing monitoring that can also be used to define the economic incentive for possible modifications or redesign of poor performing heat exchangers.

## II. Materials and Methods

Two modes of heat transfer play out in a heat exchanger, namely convection within each fluid molecules and conduction through the wall separating the two fluids [17]. In the analysis of heat exchangers, it is convenient to work with an overall heat transfer coefficient, U, that accounts for the contribution of all these effects on heat transfer. The heat transfer rate, Q, is taken to be a positive quantity and its direction is understood to be from the hot fluid to the cold in accordance with the second law of thermodynamics. The rate of heat transfer in a heat exchanger is expressed as [18].

$$Q = U \times A \times MTD \qquad (1)$$

where: Q=Heat duty, U=Overall heat transfer coefficient, W/ (m2-oC), A=Heat transfer area, m2, MTD = Mean temperature difference, oC.

The plate and frame heat exchanger used for this study was manufactured by TRANTER with a model number GXD-085-M-5-UP-267. The hot liquid employed was stabilized crude oil with water as the cold liquid. The exchanger is in continuous use with a primary purpose being to lower the crude oil temperature to an acceptable range in order to minimize flashing of hydrocarbon light ends in the storage tanks as well as eliminate impact of high temperature on its internal coating. The key design parameters are shown in Table1.

Table 1: Design and Process Parameters

| Parameter | Value |
|---|---|
| Hot Crude Oil Flow Rate | 887m3/hr |
| Cooling Water Flow Rate | 457m3/hr |
| Hot Side Inlet Temperature | 81.1$^{o}$C |
| Hot Side Outlet Temperature | 43.3$^{o}$C |
| Cold Side Inlet Temperature | 22.2$^{o}$C |
| Cold Side Outlet Temperature | 48.9$^{o}$C |
| Hot Side Velocity | 0.613m/s |
| Cold Side Velocity | 0.325m/s |
| Number of Plates | 267 |
| Total Heat Transfer Surface Area | 3 |
| Calculated Pressure drop | 0.67bar |
| Duty | 14.75MW |
| Heat Transfer Rate | 2325W/m$^{2}$-$^{o}$C |
| Mean Temperature Difference | 26.28$^{o}$C |

The analysis of a heat exchanger can be performed by either the Number of Transfer Units (NTU) method or the log mean temperature difference (LMTD) method [17]. The LMTD method is applied to problems for which the fluid flow rates and inlet temperatures, as well as a desired outlet temperature, are prescribed. Therefore, a heat exchanger modeling application that utilizes the LMTD approach was used.

### Data Gathering

The multi-year operation data of the plate and frame heat exchanger employed for the study were sourced from an oil and gas firm in Nigeria. They include the mass flow rate of the hot crude oil, mass flow rate of the cooling water, inlet temperature of the hot crude oil, outlet temperature of the hot crude oil, inlet temperature of the cooling water and pressure drop across the heat exchanger. These operating parameters were utilized with the HTRI Xchanger Suite to generate the cooling water outlet temperature, duty of the plate and frame, overall heat transfer coefficient and fouling resistance at various operating points. The values of the various operating data were detected by various instrumentation devices like the turbine flow meters, temperature transmitters and pressure gauges. The values of some parameters like the flow rates and temperatures are automatically transmitted to a system of record (SoR) called the Exaquantum which both stores the data for several years as well as provides real time values of the operating parameters at any point in time. Some other operating data like the pressure drop across the heat exchanger was manually recorded by operating personnel by reading the pressure gauges on the inlet and exit lines of the unit.

A total of over seventeen thousand data points covering the periods between 2013 and 2015 were collated from the datasheet for each of the operating parameters making it a total of 68000 data points. In addition, 1200 manually recorded data points were also used. Upon reviewing the data, some data were found to be incomplete for various reasons which included instrumentation (device) malfunction, human errors, measurement error and emergency shutdown of the facility. Based on this, the data were treated in two ways namely:

i. Incomplete data: This results when the system did not capture the values of all the key operating parameters at certain days. Due to the criticality of data completeness, days with incomplete data were removed.
ii. Outliers: Some data were provided but were found to be significantly distant from other measurements recorded and so were excluded from data set. The outliers were evaluated statistically using the Three Sigma Method denoted by equation (2) and this represented 0.07% of the overall data.

$$\alpha \pm 3\sigma \qquad (2)$$

**Development of the Heat Exchanger Model**

The model development was carried out using the Heat Transfer Research Inc (HTRI) Xchanger Suite and Parametric Study Spreadsheet. The performance parameters such as the ratio of service overall heat transfer coefficient, $U_s$, to clean overall heat transfer coefficient, $U_{cl}$, ($U_s/U_{cl}$) and the Fouling Resistance ($R_f$) were monitored. Variations in $U_s/U_{cl}$ defines the change in heat transfer capacity with time and hence the heat transfer efficiency. It was noted that tracking $U_s/U_{cl}$ alone can be misleading, because it is a hyperbolic function and hence was more reliable to monitor the fouling resistance, $R_f$, directly using the equation:

$$R_f = \left(\frac{1}{U_s}\right) - \left(\frac{1}{U_{cl}}\right) \quad (m^2\ °C/W) \qquad (3)$$

**Heat Transfer Efficiency**

The heat exchanger performance is typically measured in terms of heat transfer efficiency and hydraulic capacity [18]. In this work, the heat transfer efficiencies of the heat exchanger over a period was determined, according to [18], as the ratio of service overall heat transfer coefficient, $U_s$, to clean overall heat transfer coefficient, $U_{cl}$, both of which are defined in equations 4 and 5

$$U_s = Q/(A \times EMTD) \qquad (4)$$

$$U_{cl} = \frac{1}{\left[\left(\frac{1}{h_i}\right)\times\left(\frac{D_o}{D_i}\right)+\left(\frac{1}{h_o}\right)+R_w\right]} \qquad (5)$$

where: $U_s$ = Service overall heat transfer coefficient, (W/m$^2$ °C), Q = Rate of heat transferred, (W), A = Outside area of tubes, (m$^2$), EMTD = Effective mean temperature difference, (°C), $U_{cl}$ = Clean overall heat transfer coefficient, (W/m$^2$ °C), $h_i$ = Inside film heat transfer coefficient based on inside area, (W/m$^2$ °C), $D_o$ = Outside diameter of tubes,( m$^2$), $D_i$ = Inside diameter of tubes, (m$^2$), $h_o$ = Outside film heat transfer coefficient based on outside area, (W/m$^2$ °C), $R_w$ = Wall resistance, (m$^2$ °C/W)

Modeling the Phenomenon of Fouling Resistance

A multivariate regression method was employed to model the fouling resistance in the plate and frame heat exchanger based on the input parameters. The model shows the relationship between the fouling resistance, the crude oil mass flow rate (kg/s), crude oil inlet temperature (oC), crude oil outlet temperature (oC) and cooling water inlet temperature (oC). To predict the accuracy of the models created and subsequently determine the best performing model, the Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Percentage Error (MPE), Mean Absolute Percentage Error (MAPE), Mean Absolute Bias Error (MABE) and the Nash-Sutcliffe Coefficient of Efficiency (COE) were employed. These equations are presented as equations 4 – 9 respectively:

$$RMSE = \sqrt{\left( \sum_{i=1}^{n} (H_m - H_{cal})^2 \right) / k} \quad (6)$$

$$MBE = \left( \sum_{i=1}^{n} (H_m - H_{cal}) \right) / k \quad (7)$$

$$MPE = \frac{\left[ \sum_{i=1}^{k} \left( \frac{H_m - H_{cal}}{H_m} \right) \times 100 \right]}{k} \quad (8)$$

$$COE = 1 - \frac{\sum_{i=1}^{k} \left( H_{cal} - H_m \right)^2}{\sum_{i=1}^{k} \left( H_{cal} - \bar{H}_m \right)^2} \quad (9)$$

$$MAPE = \frac{\left[ \sum_{i=1}^{k} \left| \left( \frac{H_m - H_{cal}}{H_m} \right) \right| \times 100 \right]}{k} \quad (10)$$

$$MABE = \left( \sum_{i=1}^{n} \left| H_m - H_{cal} \right| \right) / k \quad (11)$$

Where: k = number of data points, $\bar{H}_m$ = mean of all the fouling resistance obtained from experiment.

## III. Results and Analysis

Performance of the Heat Exchanger

The accuracy of the modeling and simulation carried out using the HTRI was first determined by checking the convergence of the results to the original design parameters for the plate and frame heat exchanger. The comparison of the results from the HTRI to that of the manufacturer's design parameters are displayed in Table 2. The Table shows that the results from HTRI are very close to those of manufacturer's datasheet of the in-service plate and frame heat exchanger employed for the study. The degree of accuracy of the results therefore provides the basis for the subsequently performance study using the HTRI.

Table 2: Comparison of results from simulation with that from manufacturer's datasheet

| S/No. | Parameter | Data Sheet Value | Modelling results |
|---|---|---|---|
| 1 | Actual Heat Transfer Coefficient | 2325W/m$^2$-k | 2204.8W/m$^2$-k |
| 2 | Required Heat Transfer Coefficient | 2627W/m$^2$-K | 2282.4W/m$^2$-k |
| 3 | Duty | 14.7MW | 14.53MW |
| 4 | Area | 241.14m$^2$ | 241.27m$^2$ |
| 5 | Effective Mean Transfer Difference | 26.28$^o$C | 26.4$^o$C |
| 6 | Quantity of Plates | 267 | 267 |

The heat exchanger and the Frame in series representation are shown in Figures 1 and 2.

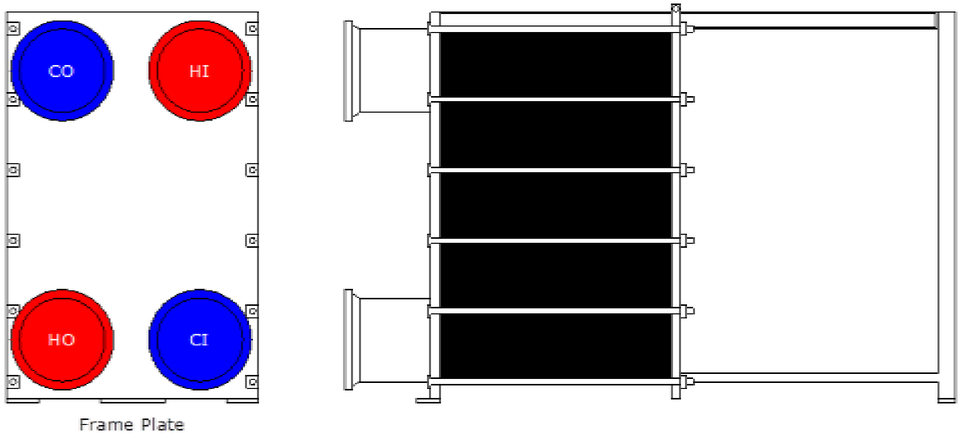


Figure 1: Heat Exchanger Drawing Showing Flow Ports

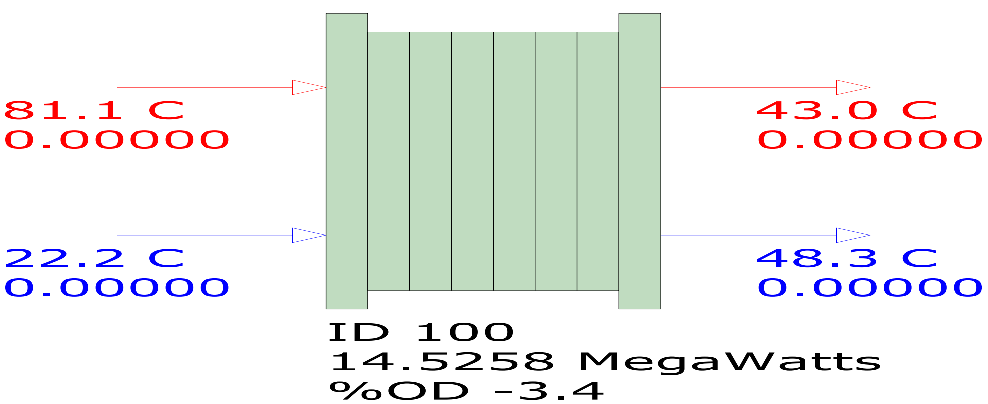


Figure 2: Frame in Series Representation of Heat Exchanger

The variations of the heat transfer efficiency over time are shown in figure 3 (a-c)

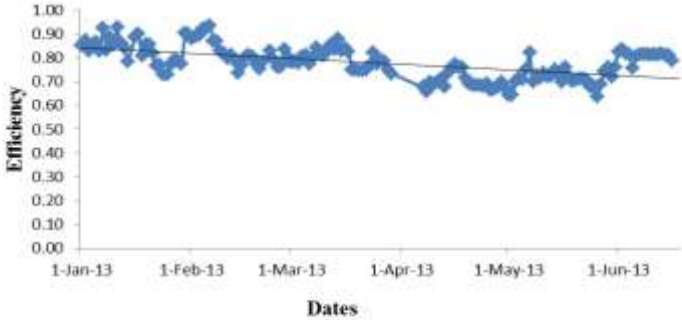


Figure 3a: Heat Transfer Efficiency of the heat exchanger (January - December 2013)

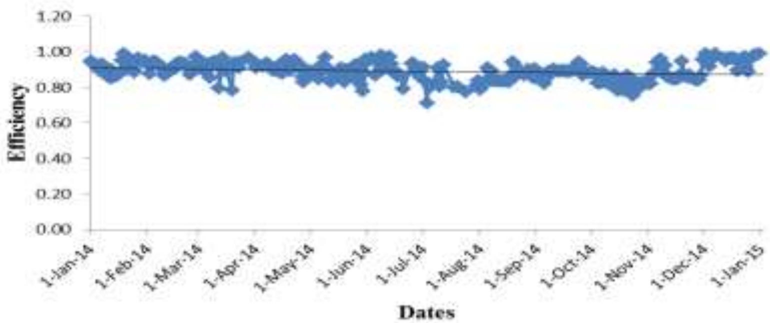


Figure 3b: Heat Transfer Efficiency of the heat exchanger (January - December 2014)

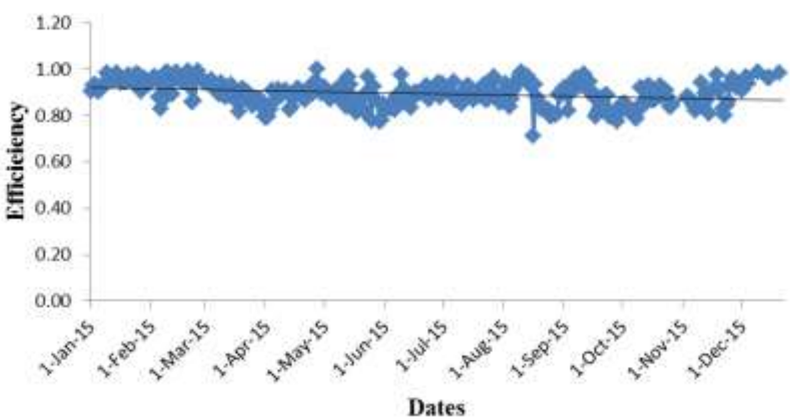


Figure 3c: Heat Transfer Efficiency of the heat exchanger (January - December 2015)

From Figure 3 (a – c), the heat transfer efficiency for each year studied tends to reduce over time. The downward trend of the heat transfer efficiency can be extrapolated to estimate when the efficiency drop would become a concern, hence facilitating early planning for possible maintenance action. The decline in heat transfer efficiency was more pronouced in 2013 than in 2014 and 2015. Based on the field data,the heat transfer efficiency was 85% as at the beginning of 2013; but it dropped to 72% by the end of the year. In 2014, the heat transfer efficiency dropped from 92% at the beginning of the year to 84% at the end of the year while in 2015 it was 92% at the beginning of the year and declined to 83% at the end of the year. The dynamic nature of the fluid properties and the process is essentially responsible for the behaviour of the efficiencies from year to year. The temperature difference was noted as responsible for the disparity in heat transfer efficiency behaviour over the years of study. The approach temperature (~average of 55$^oC$) of the crude was lowest in 2013 due to the then reservoir conditions unlike those of 2014 (~average of 58$^oC$) and 2015 (~average of 62$^oC$). Lower crude approach temperature imply lower temperature difference between the crude and cooling water and vice versa.

Moreoever, the changes in the fouling resistance $R_f$ over time are presented in figure 4 (a-c):

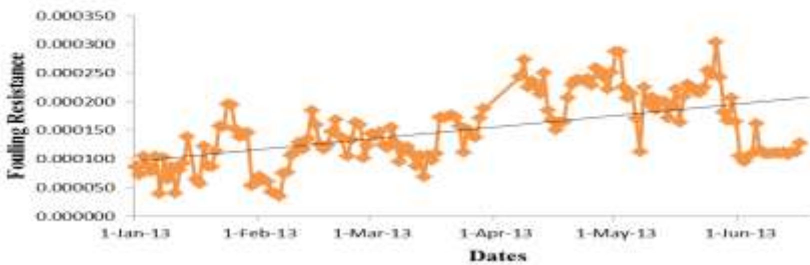


Figure 4a: Progression Fouling Resistance of the heat exchanger for the period of January to December 2013

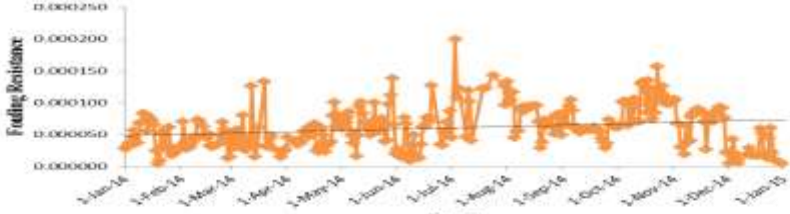


Figure 4b: Progression Fouling Resistance of the heat exchanger for the period of January to December 2014

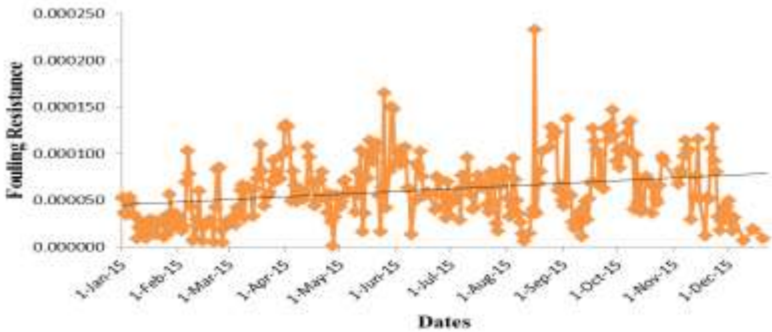


Figure 4c: Progression Fouling Resistance of the heat exchanger for the period of January to December 2015

The figure 4 (a – c) shows the fouling resistances were seen to increase over time for each year. The dynamics of the operating conditions such as changes in flow rate and variations in feed temperature were responsible for the fluctuations in data points. According to [19], fouling of heat transfer surfaces is a complex process which involves many parameters with poorly understood interactions. Hence, it could result in highly unstable processes with frequent significant fluctuation, if the variation of the heat transfer coefficient or fouling resistance was observed with time. The increase in fouling resistance over time was more in 2013 than in 2014 and 2015 respectively. In 2013, the fouling resistance ranged from 0.000035 $m^2$-K/W at 61$^oC$ to 0.000320 $m^2$-K/W at 54$^oC$. In 2014, the fouling resistance ranged from 0.000005 $m^2$-K/W at 63$^oC$ to 0.00020 $m^2$-K/W at 59$^oC$. In 2015, it ranged from 0.000005m2-K/W at 62$^oC$ to 0.000165 m2-K/W at 56$^oC$. Hence, it was observed that fouling resistance tends to increase with lower feed temperature in a plate and frame heat exchanger used for crude oil services. However, an understanding of the performance of the heat exchanger in relation to its fouling resistance is essential in order to forecast its impact on the performance and ascertain the best maintenance on the unit. This will require the development of a predictive model that explains the phenomenon of fouling resistance with input parameters. Figures 5a and 5b show the trends of the combined heat transfer efficiency and fouling resistance with time respectively.

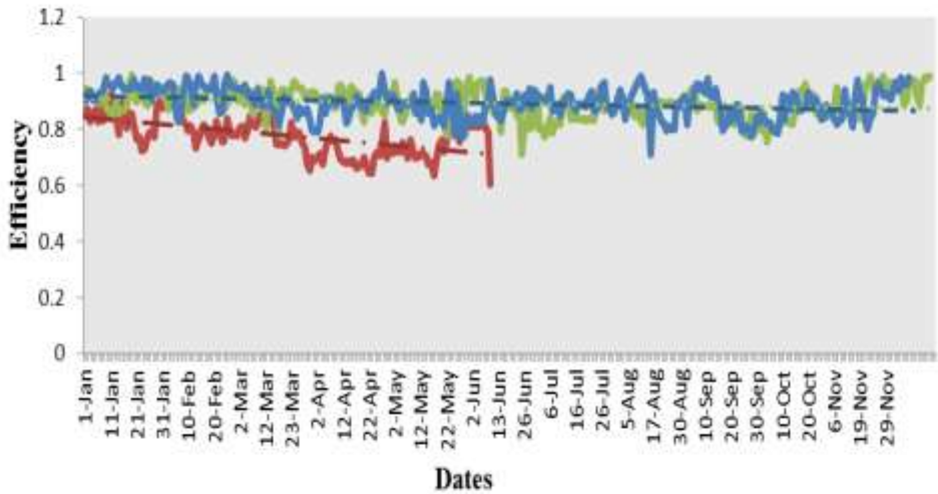


Figure 5a: Progression of Combined (Multi-Year) Heat Transfer Efficiency

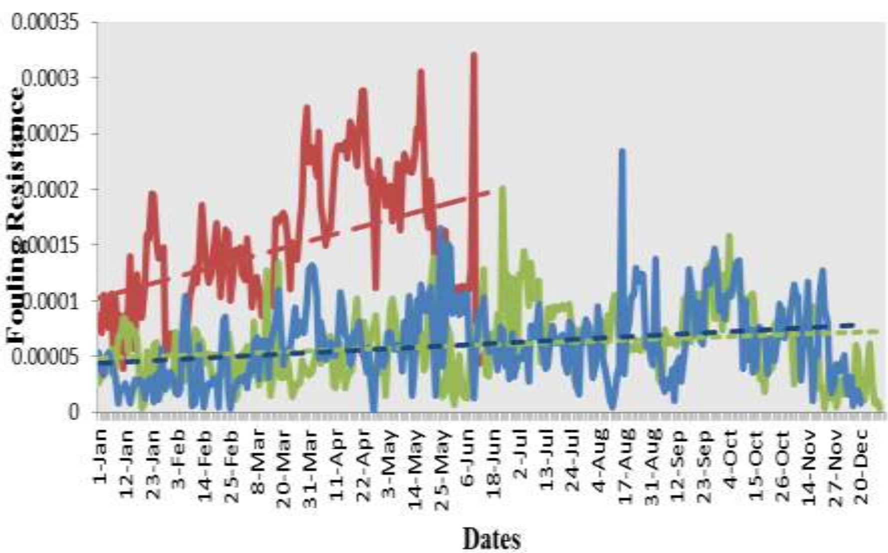


Figure 5b: Progression of Combined (Multi-Year) Fouling Resistance

***Regression Model Analysis of the Heat Exchanger Fouling Resistance ($R_f$)***

The multivariate regression models were developed using the eight hundred and eleven historical data set for the fouling resistance over time. The following modelling equations (12-16) were gotten

$$R_f = aTw_i + bTo_o + cTo_i + dM_0 + et + f \tag{12}$$

$$R_f = aTw_i + bTo_i + cM_o + dt + e \quad (13)$$

$$R_f = aM_o + bt + c \quad (14)$$

$$R_f = aTw_i + bTo_o + cTo_i + dM_o + et^2 + ft + g \quad (15)$$

$$R_f = aTw_i + bTo_o + cTo_i + dM_o^2 - et + f \quad (16)$$

where: $Tw_i$ = Cooling Water Inlet Temperature ($^0$C), $To_i$ = Crude Oil Inlet Temperature ($^0$C), $To_o$ = Crude Oil Outlet Temperature ($^0$C), $M_o$ = Crude Oil Mass Flow rate (kg/s), t = Precise Day of Operation within a specified period (day), $R_f$ = Fouling Resistance (m$^2$-K/$^o$C), and a, b, c, d, e, f, g are correlation coefficients. The values of the correlation coefficients as determined from Eqs. 12 to 16 are shown in Table 3, while those of the error and performance analysis for the different models are shown in Table 4.

Table 3: Regression Model Constants

| Coefficients | MODEL 1 | MODEL 2 | MODEL 3 | MODEL 4 | MODEL 5 |
|---|---|---|---|---|---|
| a | -2.9563E-05 | -1.49156E-05 | -2.7E-06 | -2.955E-05 | -3E-05 |
| b | 4.83066E-05 | -4.42831E-06 | -9.1E-08 | 4.82E-05 | 4.8E-05 |
| c | -1.96825E-05 | -2.57434E-06 | 0.00058 | -1.965E-05 | -2E-05 |
| d | -3.26233E-06 | -5.62769E-08 | 0 | -3.243E-06 | -9.8E-09 |
| e | -2.00747E-09 | 0.001100191 | 0 | 8.186E-12 | -1E-09 |
| f | 0.000682127 | 0 | 0 | -8.819E-09 | 0.000424 |
| g | 0 | 0 | 0 | 0.0006811 | 0 |

Table 4: Regression Model Error and Performance Analysis

| Error Term | MODEL 1 | MODEL 2 | MODEL 3 | MODEL 4 | MODEL 5 | Minimum | Maximum |
|---|---|---|---|---|---|---|---|
| RMSE | 0.8892744 | 2.0813766 | 3.7159727 | 0.8929542 | 0.87362 | 0.8736199 | 3.7159727 |
| MBE | -0.0780832 | 0.4920447 | 0.6525238 | -0.078055 | -0.074976 | -0.0780832 | 0.6525238 |
| MABE | 0.1537614 | 0.832592 | 0.9672618 | 0.1529291 | 0.158822 | 0.1529291 | 0.9672618 |
| MPE(%) | -7.8083234 | 49.204468 | 65.252375 | -7.8055016 | -7.497631 | -7.8083234 | 65.252375 |
| MAPE (%) | 0.7908089 | 4.3321284 | 13.808453 | 0.7973673 | 0.763212 | 0.7632117 | 13.808453 |
| COE | 0.9855844 | 0.6273876 | 0.4975269 | 0.9856152 | 0.983878 | 0.4975269 | 0.9856152 |
| Multiple R (%) | 99.072 | 72.272 | 59.653 | 99.074 | 98.961 | 59.653 | 99.074 |
| R-Squared (%) | 98.152 | 52.232 | 35.585 | 98.156 | 97.933 | 35.585 | 98.156 |

From the results of Tables 3 and 4, it is observed that “MODEL 4” is the best model with the coefficient of performance of 98.6% for predicting the fouling resistance of the heat exchanger. “MODEL 1” with a coefficient of performance of 98.5%" & "MODEL 5 with a coefficient of performance of 98.3 are also dependable models. Further to this, comparisons between the measured and calculated fouling resistances using each of the developed models are shown in the figures 6 (a – e).

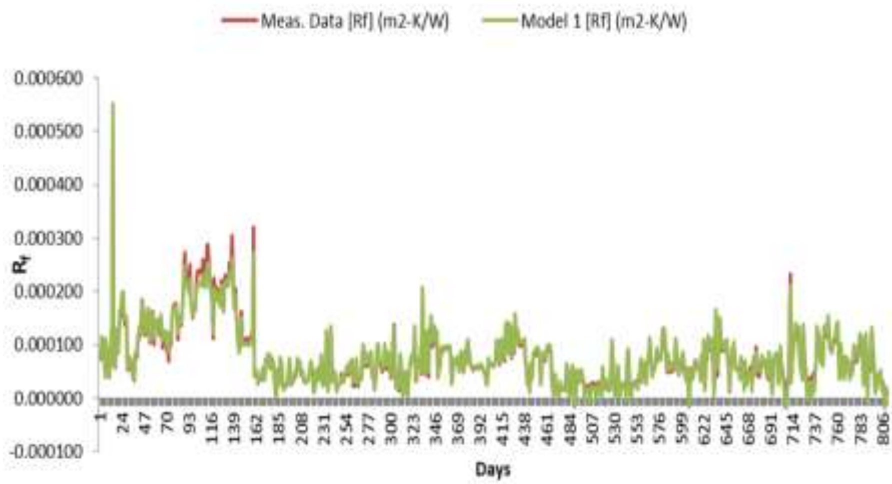


Figure 6a: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (12)

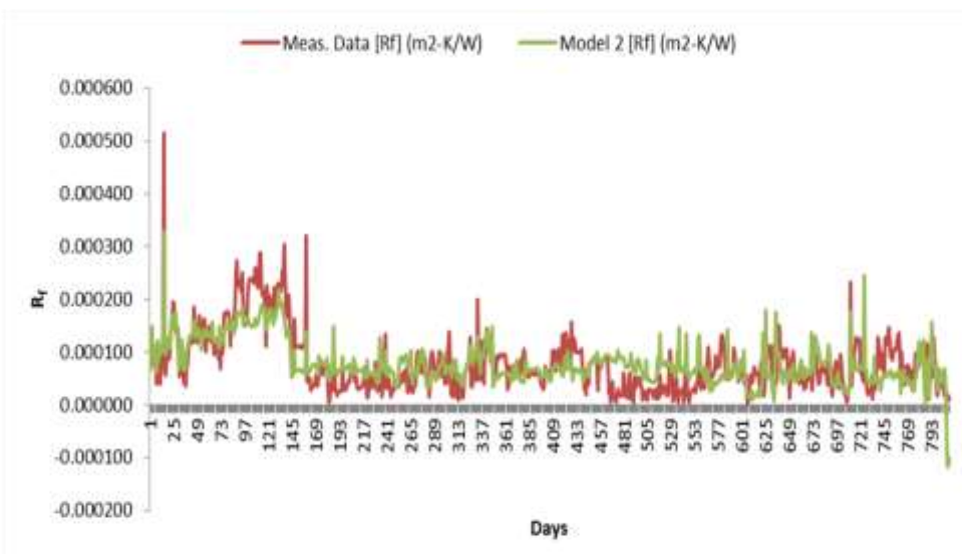


Figure 6b: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (13)

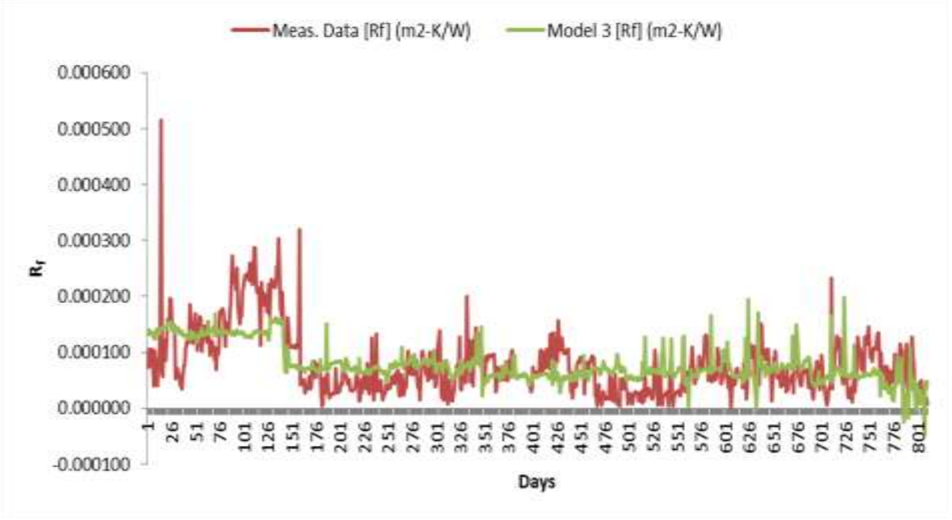


Figure 6c: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (14)

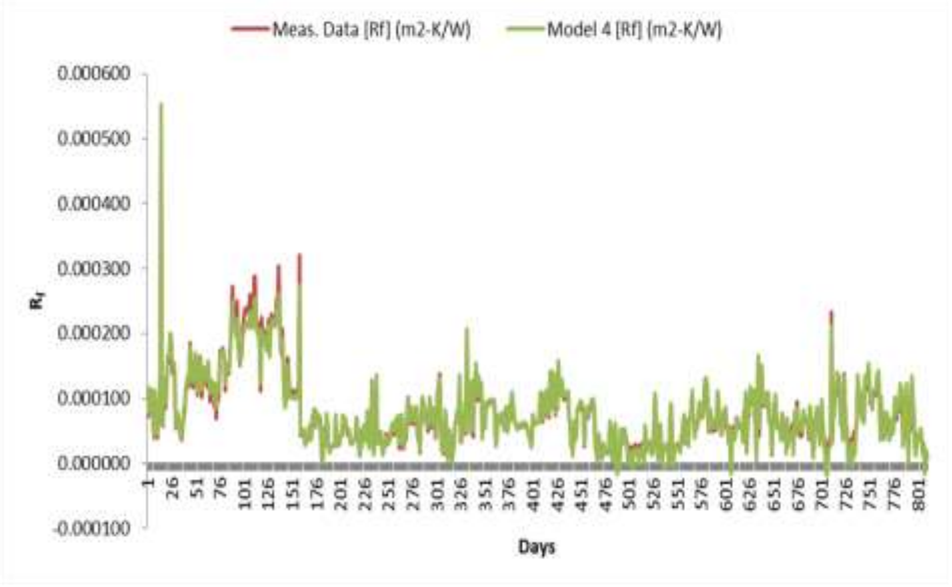


Figure 6d: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (15)

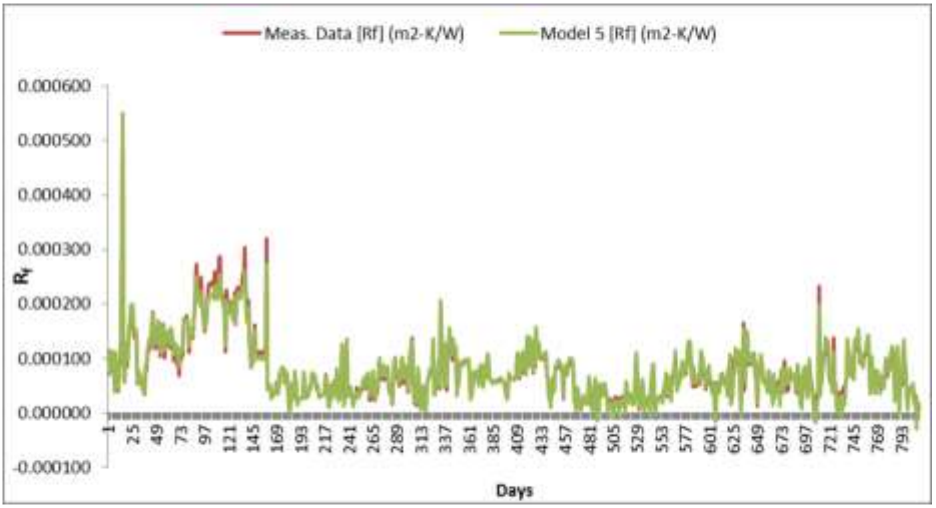


Figure 6e: Comparison between measured Fouling Resistance with calculated Fouling Resistance using Equation (16)

**Model Evaluation**

Based on the model analysis, equation (17) presents the most accurate model while equation (18) closely followed

$$R_f = \left[4.82T_\infty - 2.96T_{wi} - 1.97To_i - 0.324\ x\ 10^{-1}M_o + 8.19\ x\ 10^{-7}t^2 - 8.82\ X\ 10^{-4}t + 0.0006811\right] \times 10^{-5}$$

(17)

$$R_f = \left[4.83T_\infty - 2.96T_{wi} - 1.97T_{oi} - 0.326\ x\ 10^{-1}M_o - 2.01\ x\ 10^{-4}t + 68.21\right] \times 10^{-5}$$

(18)

Based on the aforementioned, equations (17) and (18) predict the fouling resistance of a plate and frame heat exchanger, enabling the forecast of a time when a maintenance program or any other type of intervention will be required. Table 5 therefore, provides the predicted fouling resistances of a plate and frame heat exchanger for a period (days) using the best model above at operating conditions.

Table 5: Fouling Resistance Predicted by best Regression Model

| Time (Days) | Fouling Resistance ($m^2$ °C/W) |
|---|---|
| 360 | 5.15E-05 |
| 540 | 5.13E-05 |
| 720 | 5.16E-05 |
| 900 | 5.24E-05 |
| 1080 | 5.37E-05 |
| 1260 | 5.55E-05 |
| 1440 | 5.79E-05 |

| | |
|---|---|
| 1620 | 6.09E-05 |
| 1800 | 6.43E-05 |
| 1980 | 6.83E-05 |
| 2160 | 7.28E-05 |

For instance, if a plate and frame heat exchanger is installed in January 2016, the fouling resistance would have increased to 6.43 x 10-5 m2 °C/W by January 2021. Having this knowledge will enable the operator know that heat transfer efficiency will be impacted in five years' time and then adequate plan can be put in place to clean the heat exchanger or replace with a spare unit.

## IV Conclusion

The study focused on investigation of the performance of a plate and frame heat exchanger employed in an oil and gas production/treatment facility of upstream sector with operational data. It developed multivariate regression models that can be used to predict required maintenance plan and forecast the economic implication of fouling on the heat exchanger. Apart from the results already highlighted, the study also found that at a constant cold stream temperature, the lower the hot stream approach temperature, the more the fouling resistance. Hence there is a relationship between the inlet temperature of the hot process stream and the fouling resistance. Moreover, due to the complexity of fouling phenomenon, further work may be required to develop the fouling rate models of plate and frame heat exchangers for various crudes and crude blends with different thermophysical properties and chemical compositions. Furthermore, computational fluid dynamics can be applied to the study to be able to incorporate other fluid properties and also establish the pathway to easy fouling prediction and maintenance set-up programme.

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