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TECHNO-ECONOMIC EVALUATION OF OFFSHORE OFFTAKE SYSTEMS

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***Abstract*:** This research evaluates the techno-economic constraints associated with the transport technologies and examined the comparative merits and demerits of the technologies. Three offshore offtake technologies which include oil and gas pipeline, LNG ship and shuttle tankers were evaluated using the Analytic Hierarchy Process (AHP) tool. The AHP is a multi-criteria decision making method that achieves ratio scales from paired comparisons. From the Analytic Hierarchy Process analyses and given the importance/weight of each criterion (cost, volume, time, distance and environmental impact), the Pipeline technology came out as the best and optimum oil and gas transport technology with an overall priority score of 0.8437. LNG ships came second with an overall priority score of 0.8292 while the Shuttle Tanker came third with an overall priority score of 0.6673. This study has evaluated all the pros and cons associated with each transportation technology and this report will serve as a reliable future reference material to operators, researchers and other key stakeholders in the oil and gas industry.

Key Words: Analytic Hierarchy Process (AHP), Pair wise Matrix, Overall Priority, Consistency Ratio (CR), Consistency Index.

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1. INTRODUCTION

Technologies available for transport of both oil and gas vary in maturity level and in their suitability for different transportation conditions (quantities, distances). The existing technologies permit a choice of implementation preferences to suit the quantity of hydrocarbon to be transported and the distance from field to consumer. The cost of the chain depends upon the parameters governing the fluid recovery, its transportation and its delivery. Among these parameters, the most important are the hydrocarbon volume and the transportation distance [1].

Transportation is an important aspect in the distribution of hydrocarbon products as the production centers are usually far from the market. A large proportion of the world's refineries is located far from offshore and shores. However, the fluidity of most of the petroleum products make it feasible for transportation by any mode capable of conveying a liquid from one point to another, including the use of trucks, ships and pipeline [2]. Upcoming developments in oil and gas logistics are dependent on oil and gas market enlargement, energy security and international trade laws. In general, oil and gas importing countries (typically Organization for Economic Co-operation and Development, OECD countries) have already mature oil and gas logistic infrastructure, which expansion is only considered for energy security purposes. By contrast, emerging economies such as China and India are quickly expanding their oil and gas infrastructure to meet their growing energy needs. Uncertainties on future developments of oil and gas infrastructure and possible structural changes relate to the impact of future climate policies and the recent focus on reducing greenhouse gas (GHG) emissions [3].

As stated earlier, quantity (volume) and distance are among the key parameters to determine the most suitable and profitable transportation technology for crude oil and natural gas. For larger volumes, pipeline transport is profitable for short to medium distances whereas liquefied natural gas (LNG) ship – which has 600 times smaller volume compared to gaseous phase - is profitable for larger distances[4]. The LNG technology includes natural gas liquefaction, shipping by fleets, and regasification of natural gas at the receiving terminals. The natural gas is then delivered onshore by pipelines and other distribution networks. The cost of the liquefaction plant has decreased significantly during the past decades due to improved technology and increased plant size [5]. LNG fleets are conventionally fueled with heavy fuel oil. Also, the use of ships and barges comes with associated risks, which include:

- **i.** Collisions: A barge or tanker ship hull containing crude oil can suffer severe structural damage as a result of a collision with another ship or iced berg, resulting in an oil spill [6].
- **ii.** Spill Spreading in Connecting Channels: Refineries, oil storage facilities and ports could lie along the connecting channels. Water currents and climatic

conditions pose a risk of spreading the spill into the watershed, which can complicate a comprehensive response [7].

iii. Regulatory Risks and Human Error: A special risk arises from the nature of ship and barge operations, which might not be addressed by existing regulatory measures. For instance, the movement ship and barge does not have set routes and intersections as compared to railroads or trucks. The remote dispatchers should be on guard to control seaway traffic, which increases the risk of human error leading to an accident. In addition, the current regulations may compound the risks since they rarely require the vessel operators or harbor personnel to be aware of up-to-date emergency procedures in the event of a spill [8].

iv. Impacts in Open Water: Crude spills, especially the diluent hydrocarbon (eg. Benzene) could float on the surface of the water. The ingestion and inhalation of the resulting toxic fumes can endanger seabirds and mammals. Furthermore, some crude oil samples are heavier than water, it can sink to bottom of the sea bed making the extraction process capital intensive and, in a few cases, impossible [9].

v. Impact at Shoreline: Apart from impacting the flora and fauna, the arrival of oil at the shoreline can be detrimental to the environment as well as to human coastal activities. The washed away oil that reaches coastal wetlands and beaches can severely impact commercial and sport fishing activity [10].

vi. Economic Impact: The commercial fishing industry, including fishermen and suppliers of marine related produce, can be damaged in an event of an oil spill. Concurrently small and medium businesses (especially tourism businesses) experience heavy losses due to cordon off waterways. After the clean-up, these industries incur additional expenses to retrieve lost clientele [10].

Pipelines and tankers are other viable transport technologies. Though research reveal that, by comparison with other modes of transport, pipelines have a lower incident and fatality rate per billion ton-miles of oil transported, a pipeline oil spill can have severe and long lasting impacts on the environment and regional economy [11]. The quality of pipeline infrastructure is a significant contributor to oil spill hazard. The associated risks with the use of pipelines include:

i. Pipeline Quality: Over time the efficiency of pipeline performance deteriorates due to material decay, cracks from corrosion, erosion and defective welding.

ii. Pipelines in deepwaters at extreme weather condition are subject to damage from ice, currents, floods etc which can have detrimental effects on the pipeline infrastructure [12].

iii. Monitoring: Pipelines require constant monitoring and accidents may result from undetected failures due to insufficient or delayed monitoring.

iv. Out-dated Regulatory Regime: Research show that more efficient external sensors could improve the performance of current sensors, which have detected just only five percent of pipeline spills in the U.S. [13]. However, the existing regulatory framework in most part of the world has failed to effectively enforce improved monitoring standards.

v. Physical Environment: In the ocean and deep sea, pipelines traverse diverse ecological areas including many locations that are pristine, protected areas that are sensitive to environmental degradation, and remote areas that are isolated – where there is a risk of pipeline vandalism and delayed emergency response. Both these conditions contribute to the potential risks of pipeline spills.

vi. Ecological Impact: Research indicates that floating oil spills cause death from oil ingestion in aquatic and semi aquatic mammals, and that submerged oil causes abnormalities, including spinal deformation, eye defects etc., in the newly born aquatic species [14]. A land spill can damage the top-soil or enter deep into a local aquifer, affecting the health and economic well-being of the near-by communities.

vii. Human Health Impact: The conveyed fluid sometimes evaporates rapidly in the air and can lead to high airborne levels of toxic components. This impacts the health and safety of the emergency responders as well as the surrounding communities [15].

viii. Economic Impact: In addition to the costs incurred in clean-up activities, an oil spill may negatively impact the regional economy. Either a water or land spill can result in significant economic and employment costs by putting existing jobs at risk [16].

ix. Flow assurance issues can also impacted negatively in pipeline transportation if not checked.

Tanker trucks are other options which provide flexibility, linking extraction sites and refineries to pipelines and rail terminals. As compared to other modes of transport, trucks are primarily used to transport oil for relatively short distances because long distance transport by truck is not an economical option. Their associated risks include:

i. Route collision: As likened to other transport systems, tankers operate in areas proximity to the general public and share the same infrastructure – highways, roads, neighborhoods etc. This increases the risk of accidents, including collisions and accidents at crossings, during the course of their journey. Since a collision can involve vehicles traveling at high speed, the chances of fire and explosion are higher [17].

ii. Inadequate Infrastructure: Since trucks are mostly used to convey oil to and from railway transshipment sites and pipelines, badly maintained and monitored infrastructure (bad road) at delivery points and petrol loading terminals could increase the accident level, including fire and explosion.

iii. Truck Design: While loading the oil through the bottom lines of the tanker trucks, the lines do not drain completely into the main tanks because they are at the lowest point. The structurally fragile bottom lines can contain more than 50 gallons of the hazardous liquid, referred to as ‘wetlines’, and may contribute to an event leading to fire and explosion [18].

iv. Regulatory Regime: A significant risk emerges from lack of information – for instance, the U.S. Department of Transportation does not track the total number of cargo tank trucks operating within United States and same goes for a number of other countries [19].

v. Environmental Impact: Previous experiences with truck related oil spills indicate that the biggest threat to the environment is the contamination of active water streams whose water is used for household and industrial purposes. Additionally, similar to aforementioned land and water spill impacts, the after effects of a spill can be felt on flora and fauna and on human activities [11].

vi. Impact on Human Health: Apart from the threat of air contamination, an oil spill can cause fire and explosion resulting in serious injuries and/or fatalities and loss of property.

vii. Economic Impact: An oil spill causing fire and explosion can inflict property damages that can have a long lasting impact on the housing prices of the area. Moreover, a closure to important business routes can affect businesses in the area.

The above background study provides evidence that all the modes of hydrocarbon transport pose risks that depend on a number of factors – the type of crude oil being transported, ecological vulnerability, population density, weather conditions and emergency preparedness in the region. The resulting effects may have intricate consequences for the environment, human health and economy of the region. Therefore, the operators must conduct site specific and detailed evaluation of all the transport technologies in order to select the most feasible and suitable (technical and economic wise) during field development stages. The upsurge in crude oil shipments poses safety and environmental risks from accidents that may occur along pipelines, rail lines, and waterways and at transshipment sites. All the transport technologies pose certain risks and each also has certain advantages compared with the other modes. Consequently, decisions on the transportation routes and mode of carriage are foundational to the protection of the air, land and water resources of the region. The installation of oil pipelines are long term projects, which expensive to construct and have fixed routes. Trucks, barges and vessels have less carrying volume than pipelines, but their routes are more flexible, allowing oil industry shippers to respond more quickly to changing production locations and volumes and changes in request from coastal refineries. Although pipelines have historically been the preferred choice of oil companies, these more flexible transport options can be practical and sometimes cost-effective alternatives [20]. Thus, their comparative assessment of the transport technologies prior to their deployment is highly necessary.

2. METHODOLOGY

The three offtake technologies for subsea production including: oil and gas pipeline, LNG ship and shuttle tankers were technically and economically evaluated using a multi-criteria decision making tool called Analytic Hierarchy Process (AHP) tool. The AHP achieves ratio scales from paired comparisons based on certain criteria. Here the criteria used were distance, cost, time, volume and environmental impact. The vector weights were developed from scale of relative importance subjected to satisfactory opinions using the following AHP steps.

AHP Steps [20]

1. Definition and specification of desired solution which in this case is the selection of best transport system (goal).
2. A hierarchical structure of the problem were organized with the goal at the top level, criteria placed at the 2^{nd} level and finally the alternatives at the 3^{rd} level. See Figure 1.
3. A pairwise comparison matrix was generated based on the impact of each element on each governing criterion in the next higher level and allotting values to the governing criteria was done using the scale of relative importance.
4. The pairwise matrix was normalized and the criteria weight gotten.
5. Consistency Index CI and Consistency Ratio CR were computed with $CR<0.10$ condition achieved.
6. Subsequently, the priority score evaluated.

AHP Scale of Relative Importance

a) 1= Equal Importance
b) 3= Moderate Importance
c) 5= Strong Importance
d) 7= Very Strong Importance
e) 9= Extreme Importance
f) 2, 4, 6, 8 represent Intermediate values

Allotment of Scale of Relative Importance

1. If volume = x; distance=2x, cost=4x, environmental impact=4x. This is so because, based on experts judgements consulted in this study, cost and environmental impact are the most important factors the industry considers for any technology and if distance and volume are weighed side by side, the capacity of a technology to

convey a product from point **A** to point **B** is more important than the volume it can convey. It is more reasonable to convey 100 barrels of oil twice with one technology and still get to the desired discharge point than conveying the entire 100 barrels but cannot get to the discharge point. Sequel to this, the distance as a criterion is more important than the volume. Also, if environmental impact and volume is weighed side by side, the ability to convey a product with minimal environmental impact is more important than being capable to convey large volumes of a product but with high negative impact to the environment).

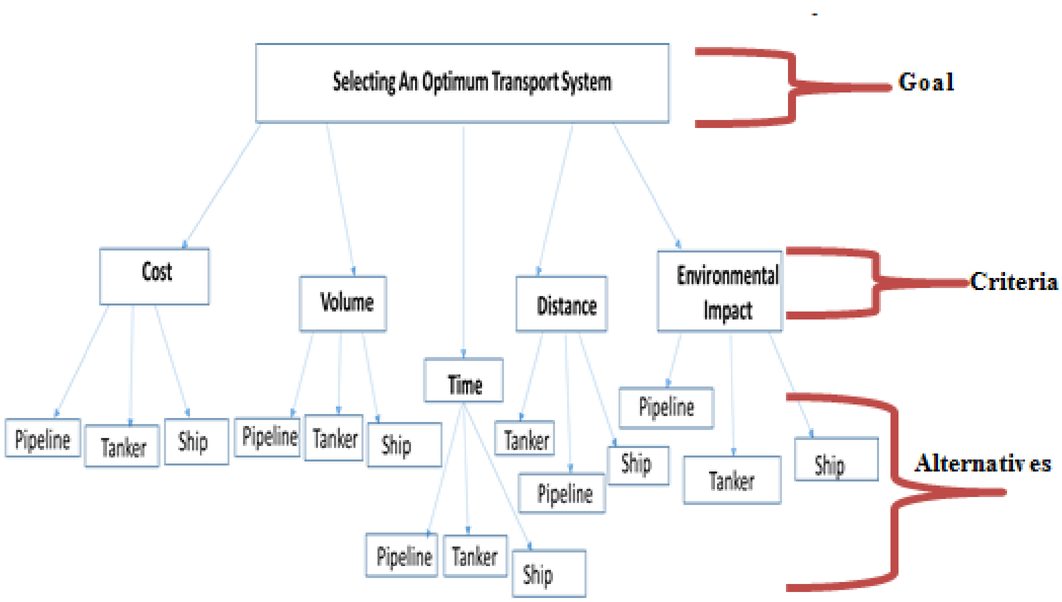

Figure 1: Hierarchical Structure

2. If time=x; volume=2x, cost=4x, environmental impact=4x. Similarly. If volume and time are weighed side by side, it is more desirable to convey 100 barrels of oil in one month from point **A** to **B** than to have a technology which can go from point **A** to **B** in one day but cannot convey the needed volumes of the product due to cost implications or any other reasons. As stated earlier, cost and environmental impact are superior to any other criterion in this present study as the end goal of the industry with respect to any technology is to break even and increase profit margin while keeping the environmental impact very minimal. Also being able to convey a product with less environmental impact is more important than how fast the product can be conveyed.

3. If distance=x; cost=4x, time=2x, environmental impact=4x. (In this case, any technology that will take less amount of time for equal volumes of product from point

A to **B** is the preferred option. Therefore, time is two times more important than distance. Also, the ability to convey a product from **A** to **B** with little or no environmental impact is more important that the distance coverable by the technology).

4. If environmental impact=x, cost=x. (As mentioned earlier, the industry will choose a technology which offers more profit and less cost and with a less environmental impact).

The implication of the assigned importance is stated in AHP step 3. 2x implies the criterion is moderately more important than the criterion it is being compared with, while 4x implies that the criterion is strongly more important than the criterion it is being compared with. Also from expert judgements and the outcome of literature reviewed the weight of each option with respect to the different criteria were derived as shown in Table 1 below:

$$\text{Cell Element} = \frac{\text{Row Element}}{\text{Column Element}} \tag{1}$$

Table 1: Pair-wise Comparison Matrix

	Attribute Or Criteria				
Criteria	**Vol**	**Dist**	**Cost**	**Time**	**Envl Impact**
Vol	1.00	2.00	4.00	0.5	4.00
Dist	0.5	1.00	4.00	2.00	4.00
Cost	0.25	0.25	1.00	0.25	1.00
Time	2.00	0.5	4.00	1.00	4.00
Envl Impact	0.25	0.25	1.00	0.25	1.00
Sum	**4.00**	**4.00**	**14.00**	**4.00**	**14.00**

3. RESULTS AND DISCUSSIONS

Table 2: Normalized Pairwise Comparison Matrix

	Attribute Or Criteria				
Criteria	**Vol**	**Dist**	**Cost**	**Time**	**Envi Impact**
Vol	0.2500	0.5000	0.2857	0.1250	0.2857
Dist	0.1250	0.2500	0.2857	0.5000	0.2857
Cost	0.0625	0.0625	0.0714	0.0625	0.0714
Time	0.5000	0.1250	0.2857	0.2500	0.2857
Env Impact	0.0625	0.0625	0.0714	0.0625	0.0714

The normalized table is generated by dividing the element of each column by the sum of the column in Table 1.

Table 3: Criteria Weight Computation

	Criteria Weight(Wc)
Vol.	0.2893
Dist.	0.2893
Cost	0.0661
Time	0.2893
Env Impact	0.0661

The criteria weight is calculated by averaging all the elements in each row of Table 2. That is, sum of the row elements divided by the number of criteria (5).

Each column element of the non-normalised matrix of Table 1 was multiplied by their corresponding criteria value to generate the consistency table show in Table 4. The summation of the alternatives in each row gives the weighted sum value as shown in Table 5

Table 4: Consistency Computation

Criteria Weights	0.2893	0.2893	0.0661	0.2893	0.0661
	Vol	**Dist**	**Cost**	**Time**	**Env Impact**
Vol	0.2893	0.5786	0.2643	0.1446	0.2643
Dist	0.1446	0.2893	0.2643	0.5786	0.2643
Cost	0.0723	0.0723	0.0661	0.0723	0.0661
Time	0.5786	0.1446	0.2643	0.2893	0.2643
Env Impact	0.0723	0.0723	0.0661	0.0723	0.0661

Table 5: Weighted Sum Computation

	Vol	Dist	Cost	Time	Env Impact	weighted Sum value(Ws)
Vol	0.2893	0.5786	0.2643	0.1446	0.2643	**1.5411**
Dist	0.1446	0.2893	0.2643	0.5786	0.2643	**1.5411**
Cost	0.0723	0.0723	0.0661	0.0723	0.0661	**0.3491**
Time	0.5786	0.1446	0.2643	0.2893	0.2643	**1.5411**
Env Impact	0.0723	0.0723	0.0661	0.0723	0.0661	**0.3491**

Table 6: Ratio of Weighted sum value to Criteria weights

	weighted Sum value(Ws)	Criteria Weights(Wc)	Ratio(R) $= \frac{Ws}{Wc}$
Vol	1.5411	0.2893	**5.3272**
Dist	1.5411	0.2893	**5.3272**
Cost	0.3491	0.0661	**5.2838**
Time	1.5411	0.2893	**5.3272**
Env. Impact	0.3491	0.0661	**5.2838**

$$\tau_{max} = \frac{\varepsilon R}{5} \quad (2)$$

$$Consistency\ Index, CI = \frac{\tau_{max}{}^{-n}}{n-1} = 0.0775;\ Number\ of\ criteria, n = 5$$

Table 7: AHP Random Index Values

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Then the Consistency Ratio (C.R) is calculated as a ratio of Consistency Index (C.I) to Random Index (R.I). The Random Index Table is shown in Table 7. From the table, Random Index value for 5 criteria is given as 1.12. Therefore, computing the Consistency Ratio gave C.R = 0.069. Since the C.R value is less than 10% (0.10) which is the standard inconsistency value, therefore our matrix is reasonably consistent and our generated criteria weight is shown in Figure 2.

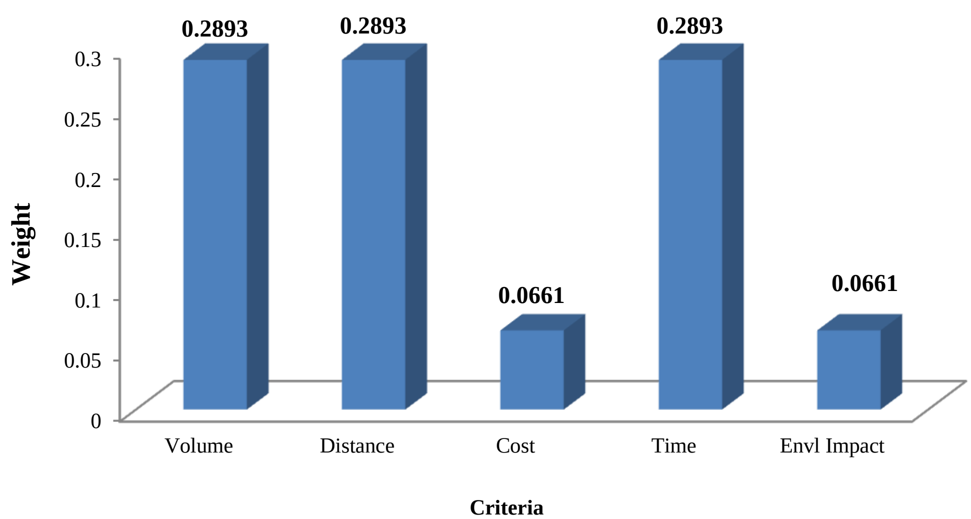

Figure 2: Validated Criteria Weight

Priority Computation

In this step, the score option values (Table 8) will be normalized by converting the matrix elements to 0-1. This is done by dividing each column element by the best criteria value on the column. The outcome of this normalization is shown in Table 9.

Table 8: Score Option Table

	Attribute or Criteria					Remarks
Alternatives	Vol	Dist	Cost	Time	Env Impact	(Score of option with respect to a criteria ranges from 1-10. 1 means poor and 10 implies excellent).
Pipeline	7	7	5	9	9	
Shuttle Tanker	5	5	9	7	7	
LNG Ships	9	9	7	5	5	

Table 9: Normalized Score of Option Values

	Vol	**Dist**	**Cost**	**Time**	**Env Impact**
Criteria Weights	**0.289**	**0.289**	**0.066**	**0.289**	**0.066**
Pipeline	0.78	0.78	0.56	1.00	1.00
Shuttle Tanker	0.56	0.56	1.00	0.78	0.78
LNG Ships	1.00	1.00	0.78	0.56	0.56

The next step is to multiply the normalized values in each column of Table 9 with the corresponding criteria weight of the column. The outcome of this step is shown in Table 10.

Table 10: Model Synthesis

	Vol	**Dist.**	**Cost**	**Time**	**Env Impact**
Pipeline	0.2257	0.2257	0.0370	0.2893	0.0661
Shuttle Tanker	0.1620	0.1620	0.0661	0.2257	0.0516
LNG Ships	0.2893	0.2893	0.0516	0.1620	0.0370

To calculate the overall priorities of the options/alternatives, the sum of the row elements in Table 10 is taken. The result is shown in Table 11.

Table 11: Overall Priorities for the Transport Technologies

Alternatives	**Overall Priority (AHP Score)**
Pipeline	0.8437
Shuttle Tanker	0.6673
LNG Ships	0.8292

Having completed the AHP analyses and given the importance/weight of each criterion (cost, volume, time, distance and environmental impact), the Pipeline technology came out on top as the best and optimum oil and gas transport technology compared to the other options with an overall priority score of 0.8437. LNG ships came second with an overall priority score of 0.8292.

4. CONCLUSION

All the transport technologies pose certain risks and each also has certain advantages and limitations compared with the other modes. However, assessment is limited by the absence of field specific data that allows researchers to analyze the distribution of costs and benefits across places in a transportation network. Therefore, this study compared the cost, time, and other constraints (including volume, environmental impact and distance) of the three different hydrocarbon fluid transport technologies for their suitability in sub-Saharan waters, particularly, for marginal field development using AHP. From the AHP analyses and given the importance/weight of each criterion (cost, volume, time, distance and environmental impact), the Pipeline technology came out top as the best and optimum oil and gas transport technology compared to the other options with an overall priority score of 0.8437. LNG ships came second with an overall priority score of 0.8292. While the Shuttle Tanker came third with an overall priority score of 0.6673.

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DECLARATION

The author declared that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article. Data for this research can be made available if requested.

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