IMPLEMENTATION OF ANALYTIC HIERARCHY PROCESS IN EVALUATION OF VULNERABLE CRITICAL OIL AND GAS INFRASTRUCTURES TO CLIMATE IMPACTS

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Abstract:

The Niger Delta oil and gas infrastructures are under severe threat of climate change impacts exacerbated by frequent flood activities, rising temperature, surging Atlantic tides, persistent heavy rainfall, and windstorms. This requires sustainable adaptation mechanisms to cope with vulnerabilities, but experts are challenged with the scale of vulnerability and ability to prioritise adaptation responses according to system criticality. Through a systematic review and synthesise of criticality assessment criteria, this paper applied multiple input analytic hierarchy process (Mi-AHP) in prioritising the criticality of seven stratified vulnerable infrastructures to ease adaptation planning. The result indicates that oil terminals, flow stations and roads/bridges are most critical infrastructures with an EV value = 0.27, 0.19, and 0.15 respectively. The result further indicated that transformers/high voltage cables are the fourth most critical systems obtaining EV = 0.14 while Pipelines, loading bays and wellheads were ranked fifth, sixth, and seventh with EV = 0.11, 0.09 and 0.05. Accordingly, the study emphasised the need for sustainable and pragmatic adaptation planning leveraging the outcome of the study to effectively manage and reduce the vulnerability of climate change impacts on oil and gas infrastructures in the Niger Delta.

Keywords: Analytical Hierarchy Process; Criticality; Oil and Gas; Infrastructure; Climate Impact Assessment; Niger Delta

1.1 Introduction

Climate change and its impacts on coastal areas have recently become a serious concern in terms of the criticality and sustainability of coastal infrastructure (Denner, Phillips, Jenkins, & Thomas, 2015; Rutherford, Hills, & Le Tissier, 2016). Coastal regions across the world host assets classed as being critical to socio-economic and environmental sustainability. The impact on any infrastructure can potentially cascade through economies, the environment, and societies. These infrastructures include telecommunications, transport systems and energy systems (where oil/gas infrastructure are in focus). In economies such as Nigeria, where oil/gas revenue constitutes about 83% of the total national revenue, 40% of GDP and 95% of exports, the oil/gas infrastructure are principally located on inundated coastal zones of the Niger Delta (Idemudia, 2012). Issues associated with climate change such as flooding, rising temperatures and the unusual rise of Atlantic tides, heavy rainfall accompanied by high winds, lightning, and thunderstorms are seriously impacting the Niger Delta (Udie, Bhattacharyya and Ozawa-Meida 2018a). These events occurring where operationally critical infrastructures are located has caused vulnerability in various degrees (Denner et al., 2015). Such extreme threats have the capacity to overwhelm infrastructure, despite the resilience and resistance, causing severe damages. Damages to critical oil/gas systems such as trunk lines and storage tanks have the potential of causing oil spills and associated ecological and social destruction (Balica, Wright, & van der Meulen, 2012). With fast-changing climatic systems, the need to systematically prioritise critical of infrastructure for focused adaptation planning is crucial (Füssel, 2007). The understanding of critical infrastructure priorities in the Niger Delta has remained fuzzy, hence the adaptation planning process lacks directional modalities and specificity. This has led to a high degree of exposure, vulnerability, and increased impact of climate-induced stressors on critical oil/gas systems. Generally, critical infrastructures comprise of facilities that provide crucial services to the economy or organisations (such as the oil/gas companies) whose operational impairment or destruction could severely affect the economic, environment, societal landscape. Other impacts include security bridging, compromise of safety, and the general wellbeing of the populace (Jagtap & Bewoor, 2017; Pursiainen, 2017).

Furthermore, asset managers lack effective climate disaster response mechanisms that prioritise critical infrastructure in the Niger Delta context. Inadequate response mechanisms have paved the way towards excessive vulnerability to extreme weather events. In practice, an attempt is being made to adapt conventional industrial disaster response and relief approaches to cope with climate-related events but often with unsatisfactory outcomes and poor management processes. The lack of empirical theoretical methodology for criteria identification and systematic multi-stakeholder evaluation of infrastructure criticality has generated considerable controversy in terms of criticality assessment within the region (Udie, Bhattacharyya and Ozawa-Meida 2018b). These issues generate only partial and reactive adaptation responses that are often easily overwhelmed by the impacts of climate change, leading to the severe damage of infrastructures. The economic relevance of oil/gas revenue and the likelihood and severity of any climate change impact underline the need for the prioritising critical asset for effective adaptation planning. The aim of this paper is to systematically evaluate and prioritise selected oil/gas infrastructure for vulnerability to climate change using an analytic hierarchy process. The objective is to provide practitioners and experts in the oil/gas industry with hands-on data on the criticality of assets with the view to ease strategic and effective adaptation planning for climate change threats on the coastal Niger Delta.

1.2 Selecting the Infrastructures

As a principle, AHP requires a fixed number of criteria and alternatives to be pairwise compared and prioritised. Overpopulation of the list of either criteria or alternatives (>7) could result in cumbersome and analysis that may invalidate result (Al Khalil, 2002; Al-Harbi, 2001; Goepel, 2013). Hence, shortlisting options could provide a condensed and focussed list of assets for consideration. Desk review of critical infrastructure in the Niger Delta shows the existence of refineries, terminals, trunk lines (12” – 30”), flow and bulk lines (6” – 8”), flow stations, wellheads, and manifolds, loading bays, gas processing plants, storage tanks, emergency diesel transformers (EDGs), high voltage cables (HVC), roads/bridges, helipads, and allied hospitality infrastructures. Stakeholder survey and field investigation resulted in shortlisted assets in Table 1 of this study.

Table 1; List of Critical Assets

Terminals	Pipelines
Flow stations	Wellheads
Loading Bays	Transformers/HVC
Roads/bridges	

2.0 Analytical review

Scoping the criteria for assessing the criticality of selected infrastructure involves a systematic review of existing literature implemented in climate change infrastructure investigations. A systematic review is a technical approach that summarises existing themes, criteria or indicator, methodologies, etc. through a strategic inclusion and exclusion of specific indices. In this study, the review included keywords from social and environmental studies of vulnerability and criticality of systems in relation to climate change impacts available from SCOPUS database. Scopus is argued to contain a comprehensive database of peer-reviewed journal articles across environmental and ecological sciences, social sciences and the built environment where criticality assessments are in focus (Shukla, Sachdeva and Joshi, 2018; Landauer, Juhola and Söderholm, 2015). Searching a single robust database in an analytical review is a theoretical strategy for eliminating duplicated journals that could arise from multiple databases (Shukla, Sachdeva and Joshi, 2018).

Frequently applied from IPCC, UNDP, World Bank and other experts' reports and academic theories were identified for this review. These include *"vulnerability assessment" OR "climate impact assessment" OR "vulnerability indicators" OR "susceptibility indicators" OR "vulnerable infrastructure" OR "adaptation assessment" OR "variability indicators" OR "climate impact indicators" AND "critical infrastructure" OR "sensitive systems" OR "coastal infrastructure" OR "criticality assessment" OR "critical infrastructure."* The first search resulted in 202 articles in related subjects' areas.

Constructed boundaries were further introduced to delineate and specify the journals. These include only peer-reviewed articles published in the English language between 2008 and 2017 and delineated to engineering, environmental sciences, earth and planetary sciences, social sciences, energy and multidisciplinary subject areas. Accordingly, 128 journal articles were filtered excluding conference papers, books and book chapters, editorials and surveys in six subject areas indicated in Figure 1.

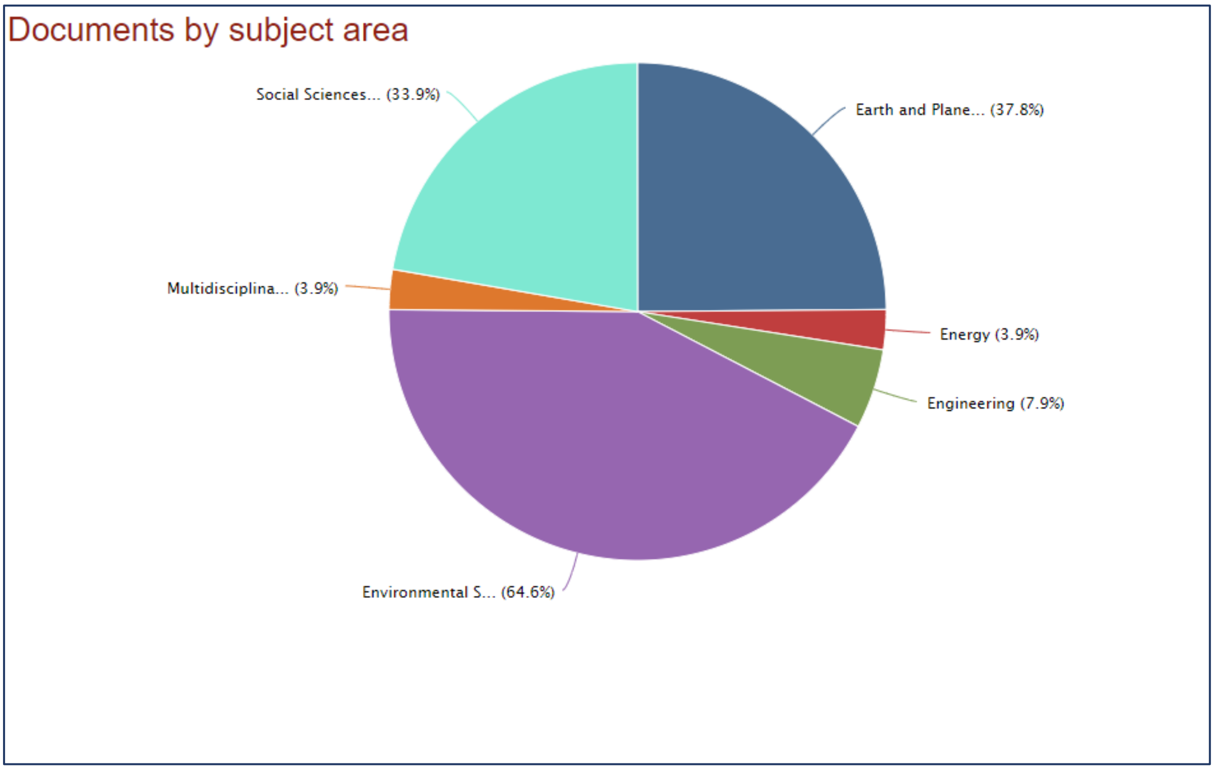

Figure 1; Source of peer-reviewed articles by year

The result shows that 64.6% of a decade of scholarly activities on criticality assessment is from environmental science while 37.8 and 33.9% arise from Earth and Planetary Sciences and Social sciences respectively. This is expected because the impact of climate change (flood, drought, etc.) are ultimately on the environment and interdependent built systems especially in coastal areas (Cabral et al., 2017; Semedo et al., 2016). The intensity of vulnerability and criticality research in the subject areas is probably due to the corresponding frequency of extreme climate change actions such as global flood, hurricanes, and temperature events and the aftermath of the 2015 Paris (COP 21) agreement.

2.1 Synthesis of criticality indicators

128 articles were exported in MS spreadsheet for further synthesis. 41.4% (53) of articles with a focus on "vulnerability" and "criticality" from abstracts and title synthesis were identified. In a separate worksheet, the papers were reviewed individually according to the following sub-themes: year of publication, study design, number of citations, keywords, study focus,

indicators/criteria used, paper type and source. Relevant statistical analysis is presented in Table 2.

Table 2; Analysis of generated subthemes

Year of Publication	Study Design			Number of Papers (%)	Average Citations (%)
	Qualitative	Quantitative	Mix		
2008 and 2009	3	0	1	7.5	13.8 (423)
2010 and 2011	6	2	3	20.8	59.0 (1,812)
2012 and 2013	4	1	2	13.2	12.2 (374)
2014 and 2015	8	2	2	22.6	12.5 (384)
2016 and 2017	11	6	2	35.9	2.5 (76)
TOTAL	32	11	10	53	3069

From the table, 32 (60%) of scholarly peer-reviewed vulnerability assessment study designs applied qualitative approaches against 20% each for quantitative and mixed methodologies. This is because most studies are sustainability driven, focusing on how climate change and environmental disaster could impact on socio-economics, human health, and environmental elements. Sustainability research is considered as critical in climate change debates (Chappells and Shove, 2005; Eriksen et al., 2011). This indicates an existing gap in the application of mix and quantitative methodologies in investigating vulnerability and criticality of infrastructures between 2008 and 2017 globally. This study adopts a mix method approach to cushion the demerits between qualitative and quantitative methods in social and environmental studies.

2.2 Criticality indicators

To identify the criteria available from review articles according to vulnerability and criticality domains, constructed synthesis was further conducted by colour coding the indicators. Criteria arising from sustainability-based assessments (environment and ecosystems, human health, income and financial implications etc.) were pink coded classed as ***criticality criteria*** while built systems-based assessment (energy, transport, telecommunication, roads infrastructures etc.) were green coded and classed as ***vulnerability criteria***. Each domain was manually counted; 56.6% were applied in criticality and 43.4% focused on vulnerability respectively. Application of MS Pro Word cloud highlighted the literature criteria according to frequency reflected in each domain (themed criteria). The "themed criteria" are adopted as principal criteria for vulnerability assessment of criticality oil and gas infrastructure to climate change impacts in the Niger Delta, using the analytic hierarchy process (AHP).

Table 3; Identified Criteria for Vulnerability and Criticality Assessment

Aggregated indicators
Interdependent infrastructure, correlated, cascading, exposure, collaborations among different expertise, Economics, Environment, expenditure, Living pattern and prevention performance, Population density, include social, economic, and human health ecosystem health and the integration of ecological systems with economic implications, social and human health factors, constraints of time, resources, Human capacity, Interlinked and supporting infrastructure, interdependence, ecosystems for human well-being, Human dependence, Ecosystem influence and interdependence, Human wellbeing, ecosystem services and human well-being, social systems, complex infrastructure, Social threats, potential menace, Regulations and environmental awareness, level of strains, Economic, Environmental factors, Social, Interdependent systems, Economic, Environmental, Physical adaptations, human practises, sustainability, socio-cultural carrying capacity, vulnerability assessment use social, economic, linkages, cultural, institutional, environmental, and physical, interdependent socio-economic factors, very high fragility, physical, environmental and socio-economic, Pressure Index, interdependent, and Fragility/sensitivity, cost, an ecological, social-ecological, sensitivity indicators, monetary impact, socioeconomic indicators, environmental, poverty, human health, key economic sectors and services, human security, and urban areas, age structure, human health, income communities, interdependence, exposure, socio-economic development, physio-chemical and biological parameters, biodiversity, ecosystems and economies and human health, Human elements, environment system, uncertainty, Historical records of burden, Age and type of building, cost of repair and Building sensitivity, ecosystems concern or communities

Figure 2; Themed criteria from literature indicators for criticality assessment

Application of criteria-based indicators in selecting from multiple alternatives occupied extensive aspects of infrastructure reviews. Tam & Tummala (2001) identified criteria for vendor selection of telecommunication systems through a desk review of available academic theories. The outcome of result aided a systematic selection of telecom vendors for respective business investments. e-Costa, Carlos A Bana & Vansnick (2008) and Rezaei-Moghaddam & Karami (2008) derived criteria for evaluation and prioritisation of sustainable agricultural models using AHP based eigenvector approach, through stakeholder engagement. In this study, a systematic review approach is adopted as demonstrated above to scope criteria that are popular in contemporary criticality assessment in line with emerging climate systems. Accordingly, seven criteria are synthesised from among the most frequent in the word cloud () and includes;

Table 4; List of Criticality Assessment Criteria

Interdependence of systems	Replacement cost
Societal Relevance	Impact on Human Health and Safety
Impact on Ecosystems	Availability of alternatives
Effectiveness of alternative	

The next section describes the implementation of AHP in the ranking of criterion weights and evaluation of the criticality of selected infrastructure. Section four analyse and discuss the result while section five presents the concluding remarks and recommendations.

3.0 Methodology

Multicriteria decision-making analysis and field investigations were conducted in the Niger Delta to obtain primary data for the study. Analytic Hierarchy Process (AHP) was implemented through a pairwise comparison process as presented in section 3.1

3.1 Implementation of Analytic Hierarchy Process (AHP)

The assessment criteria have been identified through a review of relevant literature. Seven infrastructures are shortlisted from an array of randomly scanned systems through exploratory survey and a pre-assessment engagement with stakeholders in the industry.

A four-segment AHP questionnaire was designed for data collection and determination of the weights of evaluation criteria. The principal criteria were further decomposed into sub-criteria for the prioritisation of alternatives (infrastructure). Carefully stratified field engineers, assets managers/investigators, and environmental officers in four oil/gas multinational corporations in the Niger Delta were engaged in focus groups interviews for an interdisciplinary decision-making pairwise comparison process. Data collection through focus group strategy was conducted between September and December 2016. The choice of the focus groups strategy allows for interdisciplinary contributions, eliminating controversies arising from the domination of '*personal views*. Focus group approach stimulating rigorous dialogue between participating stakeholders that elicits qualitative supporting data that strengthens the in-depth analysis. The focus groups were conducted in two parts each in four groups involving Shell Petroleum Development Company (SPDC) and Total E&P, Port Harcourt; AFCON Servicing in North Bank Flow Station, Warri; and Mobile Producing, Qua Iboe terminal (QIT) Eket.

3.2 Procedure for selecting participants

Nineteen (19) decision-makers with a minimum of ten (10) years' experience in the Niger Delta oil/gas industry were stratified as participants in focus group interviews. *Informal contacts* approach was implemented in identifying participants from the four oil companies and categorised into four (4) independent groups with each consisting of at least four (4) participants.

3.3 Procedure for implementing AHP

Advance review of relevant literature on criticality assessments, sustainability and impact assessment was conducted to scope the deconstruction processes of AHP which determination of assessment goal, and identification and decomposition criteria into sub-criteria. Combined weighting and selection of the alternatives was conducted using decomposed criteria. Evaluation of mean values (EV) was obtained by synthesising participants input using analytical hierarchy process multiple inputs (Mi – AHP) spreadsheet (Goepel, 2013) and Saaty (2008) numerical scale (Table 5).

Table 5; Saaty's pairwise comparison numerical scale for AHP evaluation

Numerical Scale	Verbal scale
1	Equal importance (*i* = *j*)
3	Moderate importance (*i* is slightly important than *j*)
5	Strong importance (*i* is strongly important than *j*)
7	Very strongly importance *(i* very strongly important than *j)*
9	Extreme importance (*i* is extremely important than *j*)
2,4,6,8	Intermediate values

3.4 Determining assessment criteria

Seven criteria from the systematic review including; interdependence of systems, replacement cost, societal relevance, impact on human health, impact on ecosystems, availability of alternatives and effectiveness of alternative; are implemented through the AHP mechanism in evaluating the criticality of the scoped system accordingly.

3.5 *Hierarchical comparison of criteria*

The seven criteria are pairwise compared to the AHP mechanism to determine each criterion weight and final hierarchy. Goepel (2015) Mi-AHP spreadsheets were used to quantitatised participant's multiple inputs. Calculated result ranking is expressed in the matrix (Figure 3) and indicates normalised principal eigenvectors as the final synthesis. The grey sections present the reciprocals values from the original data input based on the AHP principle of evaluating multiple alternatives. The dark-grey diagonal cells indicate the midpoints of comparisons (*equally important* factors of comparison).

Matrix		Interdependence 1	Replacement cost 2	Social Relevance 3	Impact on Human Health 4	Impact on Ecosystem 5	Availability of Alternatives 6	Effectiveness of Alternatives 7	normalized principal Eigenvector
Interdependence	1	-	1 2/7	1/2	1/5	1/6	2 2/5	1 2/5	7.20%
Replacement cost	2	7/9	-	3/7	1/3	1/4	1 1/2	1 2/7	6.76%
Social Relevance	3	2 1/5	2 3/8	-	1/3	2/9	3	2 2/3	12.49%
Impact on Human	4	5 2/9	3 1/3	3	-	1/2	4 1/3	5	26.10%
Impact on Ecosystem	5	6	4	4 4/7	2	-	5	5	37.24%
Availability of Alternatives	6	3/7	2/3	1/3	1/4	1/5	-	1 2/5	5.15%
Effectiveness of	7	5/7	7/9	3/8	1/5	1/5	5/7	-	5.06%

Figure 3; Showing hierarchies of criteria by AHP weights

Figure 1 indicates 'normalised principal eigenvector' weights for each criterion accordingly. It shows the capacity (by weight) of each criterion to the criticality of shortlisted alternatives. The resulting consensus of 74.1% is an indication of the high level of agreement by participants in deciding which criterion contribute more to the criticality of selected infrastructures. It also revalidates the effectiveness of AHP tool in the multi-criteria evaluation of multiple alternatives (Goepel, 2013). However, it is argued that normalised principal eigenvector (EV) values in AHP must converge to a mean value (MV = 1) expressed as the sum of geometric over 100 as shown below:

$$MV = \frac{7.2}{100} + \frac{6.76}{100} + \frac{12.49}{100} + \frac{26.1}{100} + \frac{37.24}{100} + \frac{5.15}{100} + \frac{5.06}{100} = 1$$

3.6 Hierarchical comparison of Alternatives

The criteria were applied by comparing the selected alternatives (infrastructures) through an AHP pairwise matrix mechanism. Eigenvalues for each level of analysis are indicated. The result from Mi-AHP was exported and aggregated to show the criticality ratio of each infrastructure according to each criterion.

4.0 Result and Discussion

The result of the pairwise comparison indicates an independent criterion-by-criterion priority of the criticality of seven infrastructures from Mi-AHP spreadsheets analysis. Table 6 shows the consolidated ranks as the normalised eigenvector criticality weights of each asset.

4.1 synthesis of consolidated criticality outcome

The table below presents aggregates of each criterion priority ranking computed in row/column format. It summarises consolidated criticality prioritise compared infrastructure by condensed normalisation of eigenvector (EV).

Table 6; showing aggregated AHP ranking of the 7 alternatives

Alternatives	**Total Score**	**Normalised Eigenvectors**
Terminal	189.6	27.1
Pipeline	77.7	11.1
Flow Station	129.7	18.5
Oil wellheads	35.4	5.1
Loading Bay	60.1	8.6
Transformer/HVC	99.4	14.2
Roads/bridges	108.1	15.4
TOTAL	700	100

The implication of the result is that facing an extreme weather event arising from climate change, the stakeholders in the oil/gas industry in Nigeria need to pay crucial adaptation attention to critical systems in order of their priority. It further suggests that the impact on these systems could significantly affect the indicators (criteria) according to hierarchical outcome *in* Figure 2 *and* Table 3. It implies that ecosystems, human health and safety are at the highest risk of a climate-induced extreme event in the Niger Delta. The higher an infrastructure criticality, the more impact receptor level it could receive during extreme weather events. It is deduced that the weight of a criterion is proportional to its impact on receptor capacity. The lower the criticality of an infrastructure, lessen the impact is on indicators of assessment. In this study, flood impact on terminals (27%) could impact the ecosystems (37.2%), human health/safety (26%), and the societal relevance (12.5%), etc according to their receptor capacities (weight hierarchies). Terminals, flow stations and roads/bridges ranked critically high because they are capital intensive to replace or maintain their optimal operations. This result agrees with the opinions of (Adelekan, 2010; Beg et al., 2002; Burkett, Hyman, Hagelman, Hartley, & Shephard, 2008; Haines, Kovats, Campbell-Lendrum, & Corvalán, 2006) who claimed that climate change could cause significant impact on capital-intensive sustainable infrastructure, with substantial effects on ecosystems, human population, and social architecture of communities in vulnerable coastal areas.

5.0 Conclusion and Recommendation

As indicated, the selection of infrastructure for criticality assessment with the aim of further vulnerability forecast or sustainable adaptation planning could be time-consuming and disputable amongst planners and assets managers in the oil/gas industry. The absence of prioritised data for infrastructure pose a serious challenge for planning and could exacerbate climate impact with severe consequences on sensitive sustainable indicators.

An extension of this study tests the efficiency of AHP as a scientific tool for solving complex industrial decision-making problems in the oil/gas industry by implementing a focus group strategy. This research used the AHP model for decomposing ambiguous criteria into sub-criteria via a matrix system for the ranking and selection of critical infrastructure. It is compatible with a multi-stakeholder multi-criteria decision-making assessment approach with a systematic approach to reducing controversies. Pairwise comparison placed *terminals, flow stations, roads/bridges, transformers/HVC, pipelines, loading bays and wellheads* in their order of priority in the Niger Delta for adaptation planning and further assessments. The research revealed a corroboration between critical infrastructure and sustainability indicators, which could be affected by an extreme weather event. AHP presents a flexible framework for dialogue participation amongst decision makers and demonstrates a systematic pathway for arriving at a consensus without disputatious interplay.

As the global climate continues to change with demonstrable extreme weather events exacerbating the impact on existing infrastructure, the quest for vulnerability investigation and adaptation planning could trigger the evolution of specialised techniques for assessment of critical in the industry. In this study, AHP demonstrates applicability for stakeholder use in the selection of alternatives for any purpose. It eliminates the bottlenecks associated with peer influence in focus groups of the multidisciplinary expert investigation.

The design focused on a group decision-making approach for evaluation of infrastructure criticality. A similar systematic decision-making strategy including multi-criteria multi-alternatives is required to stimulate evaluation of the vulnerability of critical assets to extreme weather impact. AHP based techniques could be employed in the identification of strengths, weaknesses, opportunities, and threats of climate change to the oil and gas industry.

This paper highlights the importance of critical infrastructure protection in the context of the oil and gas industry to relevant stakeholders (researchers, planners, engineers, environmental and assets managers). However, future research could extend investigations further to cover other activities such as transport, telecommunication, building, reservoir comparison, decommissioning, agriculture, etc. for assessment. Indicators synthesised in this investigation could be used where suitable for criticality assessment. Such an extended analysis could provide a much wider appreciation of critical assets that may be subjected to extreme weather conditions arising from climate change.

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References

Adelekan, I. O. (2010). Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization, 22*(2), 433-450.

Al Khalil, M. I. (2002). Selecting the appropriate project delivery method using AHP. *International Journal of Project Management, 20*(6), 469-474.

Al-Harbi, K. M. A. (2001). Application of the AHP in project management. *International Journal of Project Management, 19*(1), 19-27.

Aloysius, B. (2012). Floods of fury in Nigerian cities. *Journal of Sustainable Development, 5*(7), 69.

Balica, S., Wright, N. G., & van der Meulen, F. (2012). A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards, 64*(1), 73-105.

Bayazit, O. (2005). Use of AHP in decision-making for flexible manufacturing systems. *Journal of Manufacturing Technology Management, 16*(7), 808-819.

Beg, N., Morlot, J. C., Davidson, O., Afrane-Okesse, Y., Tyani, L., Denton, F., . . . Parikh, J. K. (2002). Linkages between climate change and sustainable development. *Climate Policy, 2*(2-3), 129-144.

Bloomfield, R. E., Popov, P., Salako, K., Stankovic, V., & Wright, D. (2017). *Preliminary interdependency analysis: An approach to support critical-infrastructure risk-assessment* doi:https://doi.org/10.1016/j.ress.2017.05.030

Burkett, V. R., Hyman, R. C., Hagelman, R., Hartley, S. B., & Shephard, M. (2008). Impacts of climate change and variability on transportation systems and infrastructure: Gulf coast study, phase 1, chap. 2: Why study the gulf coast. *Retrieved October 30*, 2009.

Denner, K., Phillips, M. R., Jenkins, R. E., & Thomas, T. (2015). A coastal vulnerability and environmental risk assessment of Loughor estuary, south Wales. *Ocean & Coastal Management, 116*, 478-490. doi:http://dx.doi.org/10.1016/j.ocecoaman.2015.09.002

Environmental Guidelines and Standards for the Petroleum Industry in Nigeria, (1991).

e Costa, Carlos A Bana, & Vansnick, J. (2008). A critical analysis of the eigenvalue method used to derive priorities in AHP. *European Journal of Operational Research, 187*(3), 1422-1428.

Evans, A., Strezov, V., & Evans, T. J. (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews, 13*(5), 1082-1088.

Füssel, H. -. (2007). Adaptation planning for climate change: Concepts, assessment approaches, and key lessons. *Sustainability Science, 2*(2), 265-275. doi:10.1007/s11625-007-0032-y

Goepel, K. D. (2013). Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises–a new AHP excel template with multiple inputs. *Proceedings of the International Symposium on the Analytic Hierarchy Process,* 1-10.

Goepel, K. D. (2015). AHP excel template with multiple inputs.

Green, K. P., & Jackson, T. (2015). *Safety in the transportation of oil and gas: Pipelines or rail?* Fraser Institute.

Haines, A., Kovats, R. S., Campbell-Lendrum, D., & Corvalán, C. (2006). Climate change and human health: Impacts, vulnerability and public health. *Public Health, 120*(7), 585-596.

Hák, T., Moldan, B., & Dahl, A. L. (2012). *Sustainability indicators: A scientific assessment* Island Press.

Idemudia, U. (2012). *The resource curse and the decentralization of oil revenue: The case of Nigeria* doi:http://dx.doi.org/10.1016/j.jclepro.2012.05.046

Intergovernmental Panel on Climate Change. (2014). *Climate change 2014–Impacts, adaptation and vulnerability: Regional Aspects of* Cambridge University Press.

Jagtap, H. P., & Bewoor, A. K. (2017). *Use of analytic hierarchy process methodology for criticality analysis of thermal power plant equipment* doi:http://dx.doi.org/10.1016/j.matpr.2017.02.038

Lai, V. S., Wong, B. K., & Cheung, W. (2002). Group decision making in a multiple criteria environment: A case using the AHP in software selection. *European Journal of Operational Research, 137*(1), 134-144.

Ogri, O. R. (2001). A review of the Nigerian petroleum industry and the associated environmental problems. *Environmentalist, 21*(1), 11-21.

Opukri, C., & Ibaba, I. S. (2008). Oil-induced environmental degradation and internal population displacement in Nigeria's niger delta'. *Journal of Sustainable Development in Africa, 10*(1), 173-193.

Pielke, R., Prins, G., Rayner, S., & Sarewitz, D. (2007). Climate change 2007: Lifting the taboo on adaptation. *Nature, 445*(7128), 597-598.

Pursiainen, C. (2017). *Critical infrastructure resilience: A Nordic model in the making?* doi:https://doi.org/10.1016/j.ijdrr.2017.08.006

Rezaei-Moghaddam, K., & Karami, E. (2008). A multiple criteria evaluation of sustainable agricultural development models using AHP. *Environment, Development and Sustainability, 10*(4), 407-426.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems, 21*(6), 11-25.

Rutherford, V. E., Hills, J. M., & Le Tissier, M. D. A. (2016). *Comparative analysis of adaptation strategies for coastal climate change in North-West Europe* doi:http://dx.doi.org/10.1016/j.marpol.2016.07.005

Saaty, T. L. (2003). Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research, 145*(1), 85-91.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences, 1*(1), 83-98.

Suarez, P., Anderson, W., Mahal, V., & Lakshmanan, T. (2005). Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston metro area. *Transportation Research Part D: Transport and Environment, 10*(3), 231-244.

Tam, M. C., & Tummala, V. R. (2001). An application of the AHP in vendor selection of a telecommunications system. *Omega, 29*(2), 171-182.

Tami, A. G., & Moses, O. (2015). Flood vulnerability assessment of Niger delta states relative to the 2012 flood disaster in Nigeria. *Vol, 3*, 76-83.

Udie, J., Bhattacharyya, S. and Ozawa-Meida, L. (2018a). A conceptual framework for vulnerability assessment of climate change impact on critical oil and gas infrastructure in the Niger delta. *Climate,* 6 (1), 11.

Udie, J., Bhattacharyya, S. and Ozawa-Meida, L. (2018b). Vulnerability Assessment of Climate Change Impact on Critical Oil/Gas Infrastructure: A Decision-Maker's Perception in the Niger Delta. *International Journal of Climate Change: Impacts & Responses,* 10 (4).

Ugwu, O., & Haupt, T. (2007). Key performance indicators and assessment methods for infrastructure sustainability—a South African construction industry perspective. *Building and Environment, 42*(2), 665-680.

Yu, C. (2002). A GP-AHP method for solving group decision-making fuzzy AHP problems. *Computers & Operations Research, 29*(14), 1969-2001.

Zimmerman, R. (2004). Decision-making and the vulnerability of interdependent critical infrastructure. *Systems, Man and Cybernetics, 2004 IEEE International Conference on, 5* 4059-4063.