Proceedings of the 2016 International Conference on Industrial Engineering and Operations Management
Kuala Lumpur, Malaysia, March 8-10, 2016

Development of a condition index matrix to support technical feasibility of life extension in the offshore oil and gas industry

Isaac Animah
Cranfield University, College Road
Bedfordshire MK43 0AL, UK
i.animah@cranfield.ac.uk

Mahmood Shafiee
Cranfield University, College Road
Bedfordshire MK43 0AL, UK
m.shafiee@cranfield.ac.uk

***Abstract*—A condition assessment rating tool during life extension is vital for evaluating present health status of an existing structure to facilitate decision-making. In this paper, a Condition Index Matrix methodology is proposed to justify safe continuous operation of critical assets during life extension phase within the offshore oil and gas industry. The method establishes an index called Condition Index to determine the present health status of equipment for technical justification of life extension. It combines risk assessment factors and condition indicators to produce a decision matrix. Weights are assigned to these factors through experienced field experts and literature. These weights are determined based on the severity of factors to equipment condition and risk. The weights can be modified based on particular experience of experts and the available data. Overall condition index is then calculated based on the weighted sum of the individual condition indicators. The condition index is plotted on a matrix to interpret the condition of equipment. The effectiveness of the proposed methodology is demonstrated through a case study for an oil and gas separation system on a platform. The proposed methodology can be widely applied in areas such as evaluation of life extension process, selection of end of service life scenarios, probabilistic safety assessment, and risk-informed regulations. The paper further compares the condition index matrix with aging modelling to establish its strength and weakness.**

***Keywords*—Reliability; Risk; Asset Aging, Life Extension, Structural health Assessment.**

I. Introduction

Life extension (LE) of existing offshore installations has become economically attractive over the last decade due to the decline in conventional oil and gas discovery [1]. For instance, 50% of fixed installations within the UK sector of the North Sea exceeded their original design life in 2003 [2]. The age profile of fixed installations in China also indicates that approximately 43.8% of the population would be operating beyond their original design intent by 2021 (see Fig 1). The case of Indonesia also indicates how LE has helped in the recovery of more volumes of oil in existing fields than through conventional exploration [3]. However, successful implementation of LE programmes; requires the use of appropriate methodology to technically assess and qualify existing critical asset for safe continuous operation.

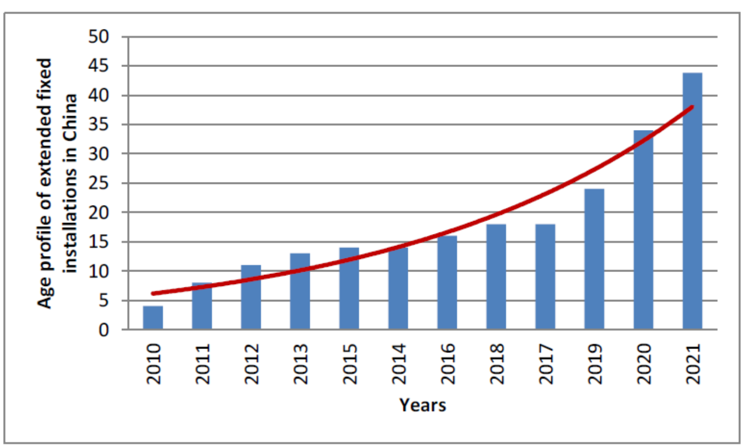

Fig. 1. Distribution of LE offshore platforms in China [4].

Many studies discussed different approaches for assessing and rating technical condition of aging assets. Analytical unavailability models incorporating aging have widely been used in the nuclear industry for assessing the current health status of safety critical equipment and support LE decision-making [5-7]. However, inability to determine the correct aging model and complex mathematical equations which require time and powerful computational programs for analysis render this approach problematic. Another approach is condition assessment rating; however, available contributions in the offshore oil and gas industry are qualitative [8, 9]. For example, Teknisk Tilstand Sikkerhet (TTS) technique has been successfully applied on thirty-five offshore and onshore installations in Norway to evaluate the state of existing safety equipment [9]. By virtue of the fact the approach is qualitative; the ability to quantitatively assess and rate current health status of critical assets is limited. It also does not consider some fundamental input factors for LE decision. Authors in the electrical utility industry have employed health indices to determine the current health conditions of power transformers [10-13], but the approach is equipment specific and not applicable to other asset types and industries.

The main aim of this paper is to present a semi-quantitative condition assessment rating methodology. The methodology focuses on systematic rating of the integrity of existing safety and production critical assets in the offshore oil and gas industry for LE. The proposed contribution is a self-assessment tool that can be used at both design and extended life phase of platform operation and also to overcome the challenge stated by [14]. The proposed methodology is similar to [8, 9]; however, we developed a comprehensive approach for rating current condition of assets based on LE decision-making inputs factors. We applied weighted scores to history and health factors in order to calculate condition index (CI), which is further used in estimating equipment current health status or predicting failure based on current conditions.

The outline of this paper is as follows: Section II presents a brief literature on condition assessment rating. Section III describes the proposed methodology for assessment rating. In section IV, we validate the proposed methodology using a numerical example. Section V discusses the result of the case study and compares CIM to other aging models. Finally, we present conclusion and future direction in Section VI.

II. CONDITION ASSESSMENT RATING

The main aim of condition assessment is to check and make judgement if the conditions of critical equipment are deteriorating [15]. In addition, condition assessment provides thorough evaluation of the physical condition of an existing facility [16]. Condition assessment methods are categorised into direct and indirect methods [17]. In order to make correct judgement for long-term operation of assets, condition assessment rating has become a major consideration to determine the extent of deterioration and subsequently seek approval from regulatory bodies. According to [18] health indices as a means of condition assessment rating represent a powerful tool in estimating the overall condition of a complex asset. In a situation where a decision maker need to select the most appropriate end of service life scenario, condition assessment rating becomes extremely important by providing vital information, since regulatory requirements alone do not provide enough insight. Ramírez, Utne and Haskins [19] suggested that researchers should support condition assessment rating with appropriate mathematical models. This research focuses on apply a semi-quantitative methodology to judge the degree of confidence in the integrity of existing critical equipment for continuous safe operation during LE period in the offshore oil and gas industry.

In order to obtain correct rating for critical equipment, the first step is to obtain available information on past and present conditions of equipment [20]. Generally, assessment rating has been achieved by benchmarking inspection and maintenance records to as-built records or experimental data or Key Performance Indicators (KPIs). Brown [21] defined KPIs as indication of how well a process or a practice is working. Chambers and Harte [22] also stated that trending of lagging KPI's (e.g. equipment breakdown frequency) would enable future conditions of equipment to be rated.

According to [23] ratings are important in establishing and prioritising actions to be taken during and after assessment. Correct assignment of rating depends on both experience and understanding of rating concept [23]. In addition, proper understanding of the operations and physics of the component or systems under assessment is also important in making correct judgment. Even though condition assessment rating scheme have existed over the years, it is applied in this paper with an exception.

III. THE PROPOSED METHODOLOGY

Limited research has been conducted into determining the condition of existing safety and production critical equipment on offshore platforms. The proposed methodology requires determination of an index called Condition Index (CI). CI represents the overall health status of safety and production critical system for LE consideration. This is achieved by grouping similar assessment factors. Similar assessment factors are grouped into historical and health factors. The minimum weight of one and maximum of four is allocated to each factor reflecting their risk contribution to equipment condition (see Table I). Each history and health factor is described into details in the following sub-sections:

TABLE I. RISK ANALYSIS SCORE CHART

Factors	Indicators	Weight	Score
Historic information	Failure history	4	
	Location	2	
	Manufacturer	2	
	Age	4	

	Environmental conditions	4	
	Total history weight	16	
Health factors	Testing	4	
	Degradation checks	4	
	Design standards	4	
	Inspection & Maintenance	4	
	Total condition weight	16	

3.1. Historical factors

Historical data is an important input for LE decision making, assisting in describing equipment performance and forecasting equipment failure. Historical factors considered are;

1. Age: Normally, offshore safety and production equipment have reliable life of about 10 -15 years [24] while the installation is designed for 20-25 years. Based on the life cycle bathtub curve, the failure rate of critical components increases at the latter stage of the asset life. Therefore, age becomes one of the risk factors for condition assessment. Also, without proper maintenance, levels of degradation increases with age of components [25, 26].
2. Failure history: This is the accumulated number of times that failures occur on equipment in a specified period. Failure resulting from degradation of equipment performance shortens lifetime of safety and production critical assets. This factor is ranked 1, when the same failure occurs twice in a calendar year. According to [27] end of service life is characterised by increased physical aging effects such as cracks, oil leaks and wear, which usually means there is risk of failure. This factor is also applicable to unplanned number of downtime and total alarm recorded in year in case of process systems.
3. Location: Equipment installed in different locations in the offshore oil and gas industry may contribute different failure rates. For example, equipment installed sub-sea are of high risk as compared to topside equipment.
4. Manufacturer: Availability of manufacturers is important due to the possibility of obsolescence which is a constraint during LE. Existence of manufacturers assures engineering team of continual supply of spare parts during LE phase of operation. Managing asset for LE requires that the necessary spare parts or critical maintenance supports are available. Hence, this is considered as a risk factor.
5. Environmental conditions: Technical condition of safety and production critical elements depends on environmental conditions in which the equipment operates. According to [15] environmental conditions about region of operation and well geographical depth have an impact on LE assessment. Nonetheless, history of wave height could also be viewed as an environmental condition, which contributes to the risk of equipment technical condition.

3.2. Health factors

Health factors considered include:

1. Test frequency: Consistent testing of critical equipment is vital in determining the current status of process equipment found on installations. The requirement to pass a test depends on the type of standards adopted by various operators. Components such as vessels and piping require pressure, temperature, hydro and Non-Destructive Testing (NDT) with frequency of testing and type of testing clearly stated.
2. Degradation checks: This health factor reflects the visual state and functional performance of equipment. Integrity checks are to identify physical ageing mechanisms and their effects on safety. An integrity check may require techniques such as visual inspection, electromagnetic inspection, fatigue inspection, ultrasonic testing and interpretations of sensor reading. Wright [2] suggested that corrosion accounts for 50% of failures in onshore process equipment. Inspection outcomes such as identification of damage mechanisms, rate of deterioration and tolerance to types of degradation is a direct means of assessing the current state safety and production critical assets for LE.
3. Design standards: This health factor evaluates the design principles of various critical equipment and compares them to current design standards and original design requirements and how they change overtime. This is to ensure that design principle meets minimum safety requirements. This activity is conducted by reviewing documents such as manufacturers' manuals, design handbooks and company internal papers. Interviewing of design professional, suppliers, installers, inspectors and project managers is also an alternative means of assessing suitability of design principles for safety reasons.
4. Maintenance: Equipment maintenance deferrals are common in the offshore oil and gas industry. Failure to inspect and maintain equipment within its scheduled time may cause failures and increase degradation rate. This health factor includes percentage compliance to corrective and preventive maintenance. Scoring this condition factor requires high level of competence and knowledge about the particular equipment.

3.3. Scores and risk ranking

Weights are assigned to the above-mentioned factors by experience field experts along with collected data over time. These weights are determined based on the severity of factors identified in Table 1 to equipment condition and risk. These weights are typically determined by field staff and they can be modified based on particular experience of experts and available data. The condition of equipment is determined by using average weighted scores by grouping similar factors and giving different weights to different group. The ranks are classified by letters A, B, C and D (see Table II for interpretations).

TABLE II. CONDITION ASSESSMENT RATINGS

Rating	Score	Risk level	Description
A	4	None	Normal
B	3	Low	Quite normal
C	2	Moderate	Not normal
D	1	High	Worse

When the scores for all risk factors have been determined, the weighted history score and the weighted health scores are calculated separately. The sum of weighted history and health scores represents condition scores. Then,

$$\text{Condition score} = \sum_{i=0}^{n} \frac{S_i W_i}{S_i}, \tag{1}$$

where S and W represent the weighted score and average weight, respectively.

Although, history factors and health factors have the same total weight (as shown in Table 1), Taengko and Damrongkulkamjorn [12] indicated that health factors reflect risk assessment more precisely than history factors. Thus, Jahromi, Piercy, Cress and Fan [13] suggested that history score should be multiplied by 40% while health score should be multiplied 60% before calculating CI. Therefore,

$$\text{CI} = (0.4 \times \text{History Score}) + (0.6 \times \text{Condition Score}). \tag{2}$$

After the computation of CI, a square matrix is developed with history CI on *y-axis* and health CI on *x-axis* where both are numbered 4 to 1 (see Fig.2). The matrix is used to determine whether LE could continue or some measures must be taken before LE approval. CI is used to rate overall asset condition based on risk contribution of each factor.

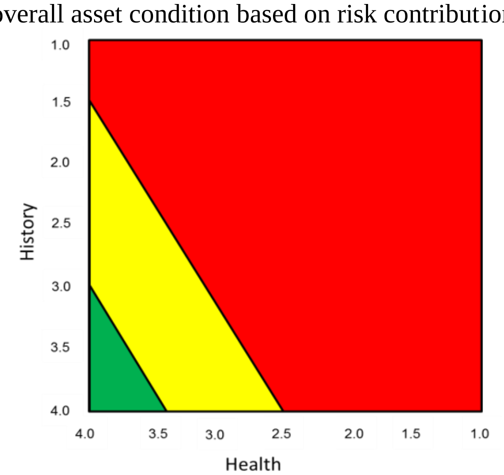

Fig. 2. Condition index matrix

3.4. Interpretation of matrix

An equipment is classified as good for LE, when the CI is between [4.0 – 3.5] on X-axis and [4.0 – 3.0] on Y-axis. This is represented by green color on the matrix, which corresponds to minimum of 3.0 of history CI and 3.5 minimum of health CI. The equipment in this category could continue with an existing maintenance regime with minimum schedule checks.

An equipment is considered to be in warning condition, when history CI is between [3.5 – 2.5] on X-axis and health CI is between [3.0 -1.5] on Y-axis and some actions must be taken before applying for LE approval. It is represented by amber color on the matrix, which corresponds to minimum of 1.5 on X- axis and 2.5 on Y-axis. The equipment will require action such as improved maintenance or safety management program (i.e. replace, repair and modification) to justify future operation. Safety/risk economic analysis must be performed to estimate the total risk cost and find the best means to ensure trade-off between safety improvement and life cycle cost.

The risk zone is represented by red color on the matrix. When equipment is found in the risk zone, it is advised that equipment must be retired out of service or extremely drastic measures must be taking for LE.

IV. NUMERICAL EXAMPLE

In this section, a numerical example is presented to demonstrate the application of the proposed methodology. Fig 3 shows a simple layout of separation system on an offshore platform, employed to demonstrate the application of the proposed method, which focusses on estimating current physical health status of safety critical elements (SCE). The function of the system is to separate three-phase well product. Separation is mainly achieved by gravity with the assistance of chemical and heat. Separated gas is routed to the gas dehydration system, which is later transported using pipelines while separated water flows into produced water treatment tank for conditioning. It is assumed that the system has operated for 25 years with an unavailability of 40% per year and requires technical justification for LE.

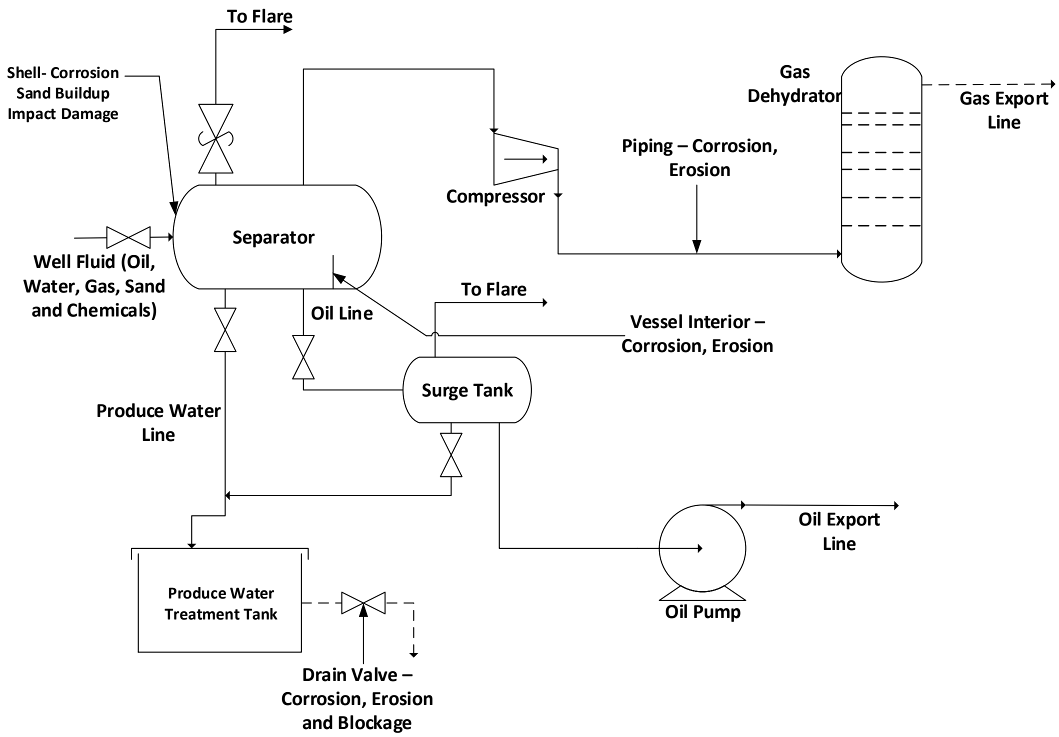

Fig 3: A typical three-phase separation system, showing degradation mechanisms

4.1. Study objectives

The objective of the study is to assess the current health condition of safety critical element (SCE) using CIM to justify their continual safe operation beyond original design intent.

4.2. System breakdown

Identification codes are assigned to each component in the system and the breakdown is applicable both at component and system level, as shown in Table III.

TABLE III. SYSTEM OR COMPONENT IDENTIFICATION

System	ID codes
Vessel (Component)	A1.A
Piping (Component)	A1.H
Pump (System)	A1.D
Compressor (System)	A1.J
Produced water treatment tank (component)	A1.E
Surge tank (Component)	A1.B
Gas dehydrator (System)	A1.C
Pressure relief valve (System)	A1.G
Drain valve (System)	A1.F

SCE present within the systems were identified using a generic list containing SCEs provided in [28-30]. A1.A, A1.F and A1.H were identified as safety critical for assessment rating. Results of test, inspection, maintenance, environmental condition, design standards, degradation trends, historical information and related KPI for assessment and scoring of SCEs were extrapolated from the following studies [21], [23], [31-33] and consultation with experts. It should be noted that these parameters may not necessarily reflect actual case but are used only to illustrate the proposed methodology.

TABLE IV. RANKING INDICATORS FOR APPLIED CASE

Historic Factors	**A**	**B**	**C**	**D**
Usage (rated capacity %)	<60	60-75	76-95	>95
Inspection (months)	<12	12	>12	>12
Failure history(number of times in a years)	0	1	2	>2
Location	-	Topside close to flammable substance	Subsea	-
Manufacturer	Still operation	Still in operation but longer produces parts	Lack of suppliers	Not in operation
Age (years)	0-3	4-10	11-20	>20
Environmental conditions		harsh	Moderate harsh	Extreme harsh
Condition factors	**A**	**B**	**C**	**D**
NDT Test frequency/yr and solid sample testing.	>2	2	1	0
Deterioration change/yr.	Constant	1%	≤4%	5%
Design conditions	Conforms to current design requirements	Conforms to original design requirements	Non-conformity to current design requirements but acceptable for safety	Non-conformity both current and original design requirement
Maintenance deferrals	0	1	2	>2

V. RESULTS AND DISCUSSION

The results of the analysis are shown in Table V. A1.A was the first component analysed. It has not recorded any faults since operation. Design standards conform to original design requirement and receive regular pressure and temperature testing. The result indicates that A1.A history CI is 1.1 while health CI is 2.1. From Eq. (2) the CI is obtained as 3.2. Plot of history and health CIs on the matrix indicated that vessel condition is in the risk zone. This means that A1.A requires an extremely drastic maintenance solutions in ensuring that the equipment qualifies for LE.

TABLE V: WEIGHTED SCORES FROM APPLIED CASE

Factors	Weight	Scores		
		A1.A	A1.F	A1.H
Failure history	4	A	D	D
Location	2	B	B	B
Manufacturer	2	A	C	D
Age	4	D	D	D
Environmental conditions	4	C	C	C
Total history score	16	2.75	1.38	1.75
Testing	4	A	D	D
Degradation checks	4	B	C	B
Design standards	4	A	A	D
Inspection & Maintenance	4	B	C	C
Total health scores	16	3.50	2.25	1.63
Total CI		3.2	1.90	1.68

A1.F was the second SCE considered for analysis. The data showed that it has recorded failure twice in a year and also failed during solid sampling analysis test. However, design conforms to current design standards. The history CI is 0.55 and health CI of 1.35 resulting in a CI of 1.90. Corresponding plot on the matrix indicates that the equipment is in the risk zone. It implies that operators should consider replacing the equipment entirely or retiring it out of service. In addition, risk and safety analysis should be performed by further assuring regulators.

The rating for A1.H produced history CI of 0.7 and health CI of 0.98, summing up to total CI of 1.68. Health information revealed that design standards for piping have evolved during the last 25 years of operation, thereby rendering piping design out of date. Also, testing, age and failure history were scored 1 based on information contained in Table II. Plot on the matrix shows that equipment is in the risk zone and actions suggested for A1.F must apply for LE. Finally, based on the SCEs' CI, the conditions are ranked as A1.A>A1.F>A1.H. The next sub-sections discuss the strength and weaknesses of the proposed method.

4.3 Comparison of CIM and other aging models

In this sub-section, we compare and discuss the proposed methodology to analytical aging models to determine the strength and weakness of the proposed methodology. Proposed methodology is compared to aging models along the lines of HSE compliance, availability of data, flexibility and time.

4.3.1 HSE compliance

CIM has the ability to identify areas of good and poor practices and enable the process of benchmarking against HSE requirements. It is designed to ensure promotion or improvement of a good practices and not restricted to ensuring compliance with HSE procedures for LE alone. According to [34] HSE encourages a strong engineering reporting line in companies and the use of CIM encourages such reporting line as compared to aging models. In addition, areas of specific damage can be identified using CIM unlike aging models which assesses existing component current health status as a function of system's availability and reliability. Other factors such as nature of production fluid, obsolescence and regulations can also impact systems availability, and not only degradation. Therefore making a decision on the condition of equipment based on availability alone may not reflect true physical health status of an asset to secure permit for extended operation [8], [24] and CIM supports this requirement.

4.3.2 Data

LE decision-making using aging models is over-reliant on data rather than good and sound engineering practices [5, 6]. CIM fills this gap by combining experts' judgement and available data, converting them into numerical values. The necessity of expert judgement for technical health assessment of critical assets for LE has already been discussed by [15]. Chambers and Harte [22] indicated that sufficient data exist to support methodologies such as CIM for aging and LE decision-making as compared to data required for aging models analysis. Application of modelling is heavily dependent on data with high degree of confidence. Unfortunately, such data for LE implementation has been identified as a challenge in the offshore oil and gas industry [32], [35]. Kančev and Čepin [6] also alluded to the fact that existing aging component database for modelling is associated with large degree of uncertainties. Therefore, decision-makers should be cautions relying on such data for analysis.

4.3.3 Flexibility

In the offshore oil and gas industry, operators need self-assessment tools to determine current health status of assets for LE [36]. Application of the aging models requires workforce with greater understanding of reliability concept, which is mostly not the case in the oil and gas industry. Also, aging models do not conclude whether equipment is in good or poor condition but rather evaluate equipment condition by determining its availability, thus not giving indication of possible end of life strategy. Due to non-flexibility of aging modelling approach, assumptions are made during analysis which sometimes does not represent the actual situation. However, risk factors' weights and scores for CIM analysis can be altered based on available data and expert's experience.

4.3.4 Time

Reliability and availability models require enormous amount of time in developing them for systems and components on offshore oil and gas installations. The time spent in developing these models may outweigh their benefit where scarce resources are available to companies. With the decline in crude oil prices, the industry needs tools which require less time for its development and application in order to operate within available budget. Thus, CIM has a comparative advantage over modelling as far as time is concerned.

VI. CONCLUSION

CIM has successfully been demonstrated using a numerical example in up-stream sector of the offshore oil and gas industry. The results of the analysis showed that CI could reflect current health condition of a system or component. Therefore, our proposed semi-quantitative tool could be used to quickly screen and assess safety and production critical element conditions for LE qualification. The results of the example showed an improvement in rating condition of existing equipment condition compared to the traditional qualitative methodologies used over the years in the offshore oil and gas industry. However, the example is illustrative and cannot be generalized, since some assumptions were used in the analysis. Also, other factors such as type of material, type of degradation and other data uncertainties were not taken into account. The example considered single component assessment rating and future application could be extended to group component.

It should be noted that risk factors, their weights and scores can be modified whenever additional data are collected or based on expert's experience. The methodology is related to physical issues of LE but to some extent cover obsolescence, human and organisational issues related to LE as compared to other approaches.

REFERENCES

[1] M. Shafiee and M.J Zuo, "Adapting an age-reduction model to extend the useful-life duration," in *International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering 2012,* 15 –18 June, Chengdu, China.

[2] I. Wright, "Ageing and life extension of offshore oil and gas installations," in *Society of Petroleum Engineers - Offshore Europe Oil and Gas Conference and Exhibition 2011, OE 2011,* 2011, pp. 842-851.

[3] N. Lowe, D. Mair, P. Markwel and J. Pettit, "A New Strategic Agenda for E&P," *Available at SSRN:,* 2014.

[4] H. Liu, X. Shi, X. Chen and Y. Liu, "Management of life extension for topsides process system of offshore platforms in Chinese Bohai Bay," *J Loss Prev Process Ind,* vol. 35, pp. 357-365, 2014.

[5] D. Kancev, B. Gjorgiev and M. Cepin, "Optimization of test interval for ageing equipment: A multi-objective genetic algorithm approach," *J Loss Prev Process Ind,* vol. 24, pp. 397-404, 2011.

[6] D. Kančev and M. Čepin, "Uncertainty and sensitivity analyses for age-dependent unavailability model integrating test and maintenance," *Nucl. Eng. Des.,* vol. 246, pp. 128-135, 2012.

[7] M. Shafiee, M. Finkelstein and M.J. Zuo, "Optimal burn-in and preventive maintenance warranty strategies with time-dependent maintenance costs," *IIE Transactions*, vol. 45, no. 9, pp. 1024-1033, 2013.

[8] E. Carvalho, F. Tang, E. Allen and P. Sharma, "A case study of asset integrity and risk assessment for subsea facilities and equipment life extension," in *Offshore Technology Conference,* 2015, .

[9] J. Ingvarson, D. N. Veritas and Ø. Strøm, "Technical safety barrier management in StatoilHydro," in *Society of Petroleum Engineers - Offshore Europe Oil and Gas Conference and Exhibition 2009, OE 2009,* 2009, pp. 732-741.

[10] M. D. M. Amir and E. S. A. Muttalib, "Health index assessment of aged oil-filled ring main units," in *Power Engineering and Optimization Conference (PEOCO), 2014 IEEE 8th International,* 2014, pp. 347-351.

[11] S. Miletic, "Asset condition assessment by health index benchmarking," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on,* 2009, pp. 1-4.

[12] K. Taengko and P. Damrongkulkamjorn, "Risk assessment for power transformers in PEA substations using health index," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2013 10th International Conference on,* 2013, pp. 1-6.

[13] A. Jahromi, R. Piercy, S. Cress and W. Fan, "An approach to power transformer asset management using health index," *IEEE Electr. Insul. Mag.,* vol. 2, pp. 20-34, 2009.

[14] H. Brandt and S. M. Mohd Sarif, "Life extension of offshore assets - balancing safety & project economics," in *SPE Asia Pacific Oil & Gas Conference and Exhibition,* 2013, pp. 165882-MS.

[15] M. Shafiee and M. Finkelstein, "A proactive group maintenance policy for continuously monitored deteriorating systems: application to offshore wind turbines," *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 229, no. 5, pp. 373–384, 2015.

[16] J. H. Bambei Jr., *Steel Penstocks.* American Society of Civil Engineers (ASCE), 2012.

[17] Z. Liu and Y. Kleiner, "State of the art review of inspection technologies for condition assessment of water pipes," *Measurement,* vol. 46, pp. 1-15, 2013.

[18] T. Hjartarson and S. Otal, "Predicting future asset condition based on current health index and maintenance level," in *Transmission & Distribution Construction, Operation and Live-Line Maintenance, 2006. ESMO 2006. IEEE 11th International Conference on,* 2006, .

[19] P. A. P. Ramírez, I. B. Utne and C. Haskins, "Application of systems engineering to integrate ageing management into maintenance management of oil and gas facilities," *Systems Engineering,* vol. 16, pp. 329-345, 2013.

[20] S. Palkar and T. Markeset, "Extending the service life span of ageing oil and gas offshore production facilities," in *Advances in Production Management Systems. Value Networks: Innovation, Technologies, and Management*Anonymous Springer, 2012, pp. 213-221.

[21] M. Brown, "Developing KPIs that drive process safety improvement," in *SPE Offshore Europe Oil & Gas Conference & Exhibition,* 2009, pp. 123845-MS.

[22] C. Chambers and H. Harte, "Data trending to support ageing and life extension(ALE) in the United Kingdom contnental shelf(UKCS) oil and gas industry," 2015.

[23] M. Shafiee (2015) Maintenance strategy selection problem: an MCDM overview, *Journal of Quality in Maintenance Engineering*, vol. 21, no. 4, pp. 378–402.

[24] E. Tveit, H. Sivertsen and S. Hernæs, "Experience from field life extension," in *Offshore Technology Conference,* 2014, .

[25] S. Kumar, R. Dandotiya, R. Kumar and U. Kumar, "Inspection frequency optimization model for degrading flowlines on an offshore platform," *Int. J. Reliab. , Qual. Saf. Eng.,* vol. 15, pp. 167-180, 2008.

[26] R. H. Gunderson, A. Stevenson, J. A. Harris, P. Gahagan and T. S. Chilton, "Fatigue Life of TLP Flexelements," /1/1/, 1992.

[27] H. Picard, J. Verstraten, M. Hakkens and R. Vervaet, "Decision model for end of life management of switchgears," in *Electrical and Instrumentation Applications in the Petroleum & Chemical Industry, 2007. PCIC Europe 2007. 4th European Conference on,* 2007, pp. 1-10.

[28] M. Cortina, E. Pavli, G. Antinolfi, L. La Rosa, I. Rainaldi and A. Petrone, "An overarching strategy for safety critical elements assessment and management," in *Society of Petroleum Engineers - SPE International Conference on Health, Safety and Environment 2014: The Journey Continues,* 2014, pp. 984-1011.

[29] P. Horrocks, D. Mansfield, K. Parker, J. Thomson, T. Atkinson, J. Worsley, W. House and B. Park, "Managing ageing plant," HSE, Warrington, UK, Tech. Rep. 823, 2010.

[30] D. N. Veritas, *OREDA-Offshore Re-Liability Data Handbook 2009.* H (Φ) vik: DNV, 2009.

[31] OLF, " Norwegian oil and gas recommended guidelines for assessment and documentation of service life extension of facilities," 2012.

[32] P. Hokstad, S. Habrekke, R. Johnsen and S. Sangesland, "Ageing and life extension for offshore facilities," SINTEF Technology and Society, Norway, Tech. Rep. A15322, 2010.

[33] NORSOK, "Process systems, P-100," 2001.

[34] T. Powell, "3-year study by UK regulators concludes industry must increase focus on asset integrity," *Drilling Contractor,* vol. 64, 2008.

[35] P. A. P. Ramírez and I. B. Utne, "Challenges due to aging plants," *Process Saf. Prog.,* vol. 30, pp. 196-199, 2011.

[36] D. N. Galbraith, J. V. Sharp and E. Terry, "Managing life extension in aging offshore installations," in *Offshore Europe Conference - Proceedings,* 2005, pp. 453-461.

BIOGRAPHY

Isaac Animah is currently a PhD srtudent in the School of Energy, Environment and Agrifood (SEEA), Cranfield University, UK. He received his MSc degree in offshore and ocean technology with Subsea Engineering from Cranfield University in 2012. His research interest includes risk assessment, safety engineering, reliability analysis, maintenance management and condition assessment.

Mahmood Shafiee is a Lecturer in Engineering Risk Analysis at Cranfield University, UK. His expertise is in the fields of Reliability Engineering, Maintenance Optimisation, Inspection Planning, Residual Life Prediction & Extension, Structural Health Assessment, Aging and Degradation Modeling, Probabilistic Risk Analysis, Risk-based Integrity, Decision Making under Uncertainty, Infrastructure Asset Management, Warranty & Service Contracts Analysis, and Maintenance Logistics. Dr Shafiee has over ten years of experience in the area of Risk and Reliability Engineering within the Oil and Gas, Offshore Renewable Energy, Railway Transport, Manufacturing and the Finance Industry Sectors. He has been awarded with several honors and educational scholarships at the national and international levels. He was recently nominated in Marquis Who's Who which contains biographical information on outstanding achievers worldwide. Dr Shafiee has published more than forty papers in top tier journals like *European Journal of Operational Research*, *Reliability Engineering and System Safety*, *IEEE Transactions on Reliability*, *Renewable Energy*, *Journal of Rail and Rapid Transit*, *Journal of Risk and Reliability*, *Expert Systems with Applications*, *International Journal of Advanced Manufacturing Technology*, *IIE Transactions*, *Energies*, as well as many Conference Proceedings. He has also been Program Committee member of a number of international workshops and conferences.