International Journal of Energy and Environmental Research, 12 (1), 19-34, 2024
Print ISSN -2055-0197(Print),
Online ISSN 2055-0200(Online)
https://www.eajournals.org/
Publication of the European Centre for Research Training and Development -UK

Development of Process Safety Cumulative Risk Assessment in Niger-Delta Region, Nigeria

Mobolaji Adekunle Popoola
Bachelor of Science in Electrical and Electronics Engineering
Obafemi Awolowo University, Nigeria
hinadanish1990@yahoo.com

doi:https://doi.org/10.37745/ijeer.13/vol12n11934 Published March 24, 2024

Citation: Popoola M.A. (2024) Development of Process Safety Cumulative Risk Assessment in Niger-Delta Region, Nigeria, *International Journal of Energy and Environmental Research*, 12 (1), 19-34

ABSTRACT: *One of the key challenges in preventing major process safety accidents in an operating plant is the lack of an integrated system/model that brings together the risks posed by the deficiencies / deviations on the safety critical barriers, for operational decision making. Based on this context, an exploratory study was undertaken to develop a model/framework for visualizing the accumulation of process safety risks arising from safety critical barriers impairments in petroleum facilities in Niger-Delta Nigeria. The results indicate that the process safety cumulative risk assessment framework/model offers a transparent mechanism for assessing and visualizing the cumulative risks arising from the barrier impairment problems. For the facility in the first case study, 3.2% of the total number of safety-critical barriers was deviated and the model revealed risk accumulation in the gas compression functional location. For the facility in the second case study, 1.7% of the total number of safety-critical barriers was deviated and the model revealed risk accumulation in the gas dehydration functional location. When applied properly, the model/framework will reduce the risk of major accident in petroleum facilities by (a) aiding better management of safety critical barriers deviations through improved risks visual and (b) eliminate variability in human interpretation of process safety risk levels. One improvement area identified in the model/framework is the need for a web-based software for automation of barrier impairment data collection and real-time visualization of the cumulative risk picture.*

KEYWORDS: process safety, cumulative risk assessment, risk visualization, major accident prevention, petroleum operations

INTRODUCTION

Process safety accident is typically defined as “an event that is potentially catastrophic, involving the release/loss of containment of hazardous materials that can result in large-scale health and environmental consequences” [1] and serious injuries/multiples fatalities and loss production [2]. Globally, it is recognized that major process safety accidents have been occurring in petroleum facilities [3]. Despite the various efforts to curb the occurrence of these incidents, significant accidents still occur. The petroleum sector has witnessed a significant number of process safety incidents [4] and these major accidents are usually investigated, and recommendations made. Majority of major accident investigation reports as noted in a previous study indicate that the concerned organizations were faced with numerous safety critical barrier impairment challenges during the operational stage of the assets, however the signs were either overlooked or simply not handled appropriately [5]. Mechanical integrity failures have been the contributor to 40-50% of these accidents and impairment of safety barriers during the operating lifecycle of a plant has also been implicated [6]. In most of these major accidents, there was accumulation of process safety risks arising from the barrier impairments, preceding the incidents [5, 7] but plant operators were blind-sided to the cumulative risk impact of the deviations [8]. Most of these anomalies in the plant were known by the organization but the cumulative risk of the gaps were not understood [5]. Often the information is not transparent to the people who have the responsibility to intervene. It was pointed out that 60% of companies are not managing pro-actively the impaired safety critical barriers in their facility because they do not have effective systems in place to monitor and manage the barrier impairments [9]. It was also noted that there were often insufficient measures to recognize the barrier impairments and prevent the propagation of the incidents [10]. Risks arising from a single safety critical impairment is usually understood but with multiple barrier impairments on a plant, it is essential to understand the changing overall risk profile of the plant, from a "cumulative risk" perspective [11] and have a means to provide the assurance that major hazard risks are adequately controlled [12]. Therefore, the aim of this study is to develop a model/framework for assessment of process safety cumulative risk, to reduce major accident risk in petroleum operations by offering petroleum industries a risk-based approach to understanding and managing safety critical deviations and using risk-based decision making to better prioritize plant maintenance, optimize work execution and improve productivity.

In process safety risk management, risk controls/barriers have to work as intended. Once a control/barrier is impaired (not working as intended), it represents a "deviation". When there are multiple deviations, the risks presented by the deviations accumulate (cumulative risk) and may pre-dispose the plant to a major accident. The combined effect of risks from multiple deviations, impacting the safety of a plant is termed as cumulative risk [13].

LITERATURE REVIEW

Numerous models have been developed by industry professionals to significantly reduce the frequency and severity of such catastrophic accidents by proper risk assessments [14]. However, most of these models are based on traditional risk assessment approaches and these have the drawback of being static and not keeping up with the modifications that occur in the operating phase of the asset [15, 16]. Some models are based on quantitative approaches that incorporates mathematical quantification with many drawbacks [17]. For operational decision making on major accident risk, quantitative risk assessment can be problematic because of their size and complexity, making them difficult to use on a day-to-day basis [18]. Table 1 summarizes the gaps found during the literature review. The need for a "living" risk assessment model that takes into account factors like safety critical deviations during the operating phase of plants have been recognized [3, 23]. The model should have the capability to assess the health of the safety critical barriers on a near real-time basis [23, 5] and present the assessment in a very visible and transparent form at all levels from front-line to top management, across all areas of the plant, for decision support in ongoing operational risk management [7]. Even though there are many studies in process safety management for major accident prevention [26], however there are few studies that consider the concept of process safety cumulative risk assessment in the petroleum operations [27].

In the recent past, some Operators in the oil and gas industry have developed their own proprietary tools for integrated management of safety critical information across their facilities, for example iSee from ConocoPhilips Total Risk [28]. Literatures on these works are scant.

METHODS

The aim of this study was to develop process safety cumulative risk assessment framework/model for major accident prevention in petroleum operations. To achieve this aim, two objectives were pursued. One objective was to develop process safety cumulative risk assessment logic/rule while the other objective was to develop process safety cumulative risk assessment framework/model and validate the framework/model using two case studies.

The study builds on previous works performed by the author. A previous study identified seven risk elements/influencing factors that are to be considered in assessing process safety cumulative risk viz: preventive maintenance deviations, corrective maintenance deviations, temporary changes/repairs, inhibits/overrides, down-graded integrity items, open actions from safety audits/reviews and hardware barrier assessments. Another study established that the use of "traffic light" scoring system to represent impairment on a safety critical barrier is simpler and less complex than using mathematical/quantitative risk assessment models.

Table 1. *Summary of literature review contributions and gaps.*

S/N	Title	Contribution	Gaps	Reference
1.	Guidance to improve the effectiveness of process safety management systems in operating assets	The work identified risk influencing factors for process safety incidents, based on the experience of the author, literature reviews and incident investigation reports	The results indicated that the current process safety risk models do not take into due consideration of the risk factors	[3]
2.	Advanced safety methodology for risk management of petroleum refinery operations	The study identified that there is a lack of robust risk management tools to identify and assess major accident risks and proposed a quantitative risk modelling	The risk management framework for refinery operations was based on complex and static quantitative risk assessment approaches which	[19]

S/N	Title	Contribution	Gaps	Reference
		framework for petroleum refinery operations	are not suitable for daily operational risk management	
3.	Visualizing risk related information for work orders through the planning process of maintenance activities	The work developed a computerized display for the concept of how risk related information can be visualized in an operational context when establishing work orders	The results covered only work orders in maintenance activities and did not cover all other risk factors for major accidents in daily operations	[20]
4.	Dynamic barrier management – managing safety barrier degradation	The study developed a barrier management model that enhances safety decisions while reducing inspection costs and proposed a quantitative risk modelling framework for oil and gas facilities	The barrier management model was based on complex and static quantitative risk assessment approaches which are not suitable for daily operational risk management	[21]
5.	Development of an integrated process safety management and climate change model for the oil and gas industry	This study developed a model integrating all the process safety management systems into a holistic model, addressing process risks posed to oil and gas operations including external factors such as climate change.	The implementation structure for the development of the model was around three risk-based, culture-based and external factors, integrating CCPS risk-based elements with external factors such as climate change. This model is not suitable for management of process safety risks in daily operations	[22]
6.	Barrier management in operations for the rig industry	The study developed a framework for barrier management in rig operations, basically showing how barrier performance can be maintained. The study recommended developing systems that capture early warnings and indicators	The framework does not contain requirements for barrier dependencies and interactions as part of the barrier performance requirements and risk factors. The study did not develop any framework or model.	[23]

S/N	Title	Contribution	Gaps	Reference
		about deterioration of barriers		
7.	Activity-based risk analysis for process plant operations	This study developed a model MIRMAP (Modeling Instantaneous Risks for Major Accident Prevention) to give up to date risk information with limited effort and sufficiently quickly to be available when decisions are being made	Key drawback of the tool is in its complex nature by using quantitative risk assessment (QRA) methodologies, even different from the traditional QRA approaches	[24]
8.	Barrier status panel – tool for barrier management	The model developed a "barrier status panel", a web-based tool that helps to monitor and verify barriers at all times	The model is limited on the number of risk factors and has not capability to visualize cumulative risk picture	[25]

Qualitative research techniques were used. Qualitative data was gathered through focused workshops (focused asset integrity and process safety professionals). The study data was obtained from both primary sources (focused asset integrity and process safety professionals in Nigeria with minimum of 15 years' process safety experience in petroleum operations) and secondary sources (process safety journal articles and petroleum industry operating manuals). The data was analyzed using qualitative techniques such as content analysis. Two case studies were selected by convenience sampling, to test the results of the model/framework. Field data was gathered from an offshore Floating Production Storage and Offloading (FPSO) facility and onshore gas processing plant through field visits. Validating the model/framework was carried out in a workshop by the focused asset integrity and process safety professionals using a "formal process of member checking" method [29], by sharing the data with the number of people from whom the data was drawn.

RESULTS

Development of Process Safety Cumulative Risk Assessment Logic/Rule Set

Figure 1 shows the integrated process safety cumulative assessment logic/rule set, developed based on the risk assessment processes in daily operations of petroleum facilities. For every deviation on the seven risk factors, the final outcome of the risk rating from the logic/rule will become either Green, Amber or Red, depending on the applicable decision types:

1. Risk priority which is analyzed using the risk assessment matrix of the organization on a 2-scale priority – High or Low
2. Deviation validity date which is checked for exceedance of the Latest Allowable Finish Date (LAFD)
3. Impact on the deviation (High/Low) on the integrity of the barrier in question
4. Deviation approval status
5. Status of implementation of the approved action (within the agreed dates)

Development of Process Safety Cumulative Risk Assessment Model/Framework

The strategy adopted in the development of the process safety cumulative risk assessment framework/model was structured around data input for process safety cumulative risk assessment, data aggregation and data output. Figure 2 shows the framework/model. The framework/model works in three stages:

1. Data collection on every safety critical barrier using the seven risk factors
2. Barrier data analysis using the logic/rule set and mapping on major accident bowties of the respective functional location
3. Visualizing cumulative risk for possible risk accumulations

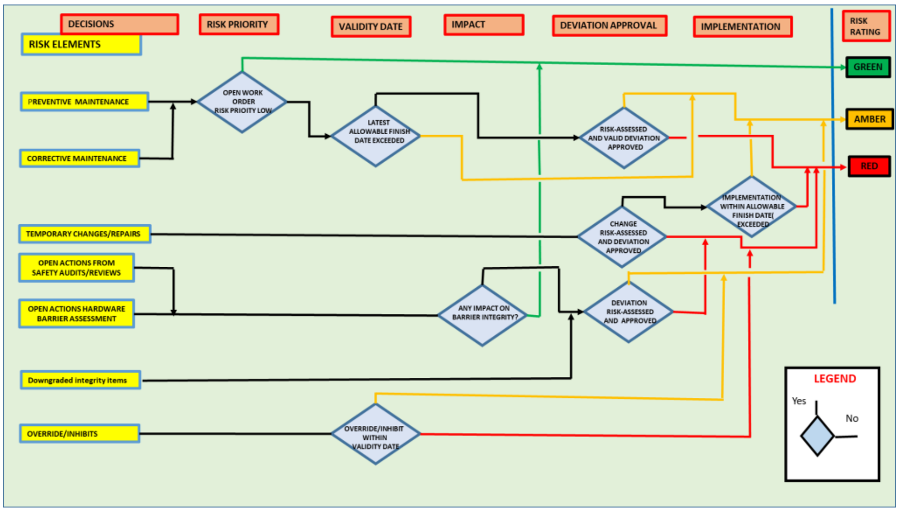

__Figure 1.__ Integrated Logic/Rule for assessing process safety cumulative risk.

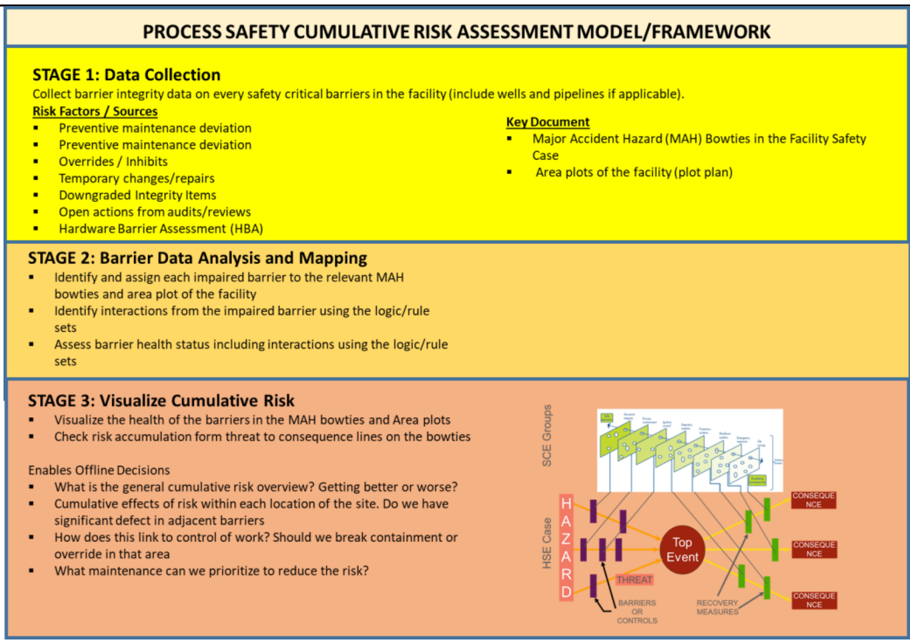

Figure 2. *Process safety cumulative risk assessment model/framework.*

Case Studies

Two facilities were used for the case studies – a Floating Production Storage and Offloading (FPSO) facility offshore Nigeria and a gas processing facility onshore Nigeria.

Case Study 1 - Application on FPSO Facility Offshore Niger-Delta Nigeria

A site visit to the FPSO facility was conducted. At the time of the visit to the facility: 65 preventive maintenance deviations, 14 corrective maintenance deviations and 35 temporal changes/repairs and overrides/inhibits were identified. Figure 3 shows the distribution of the deviations in the FPSO facility. Out of the 3,557 tags in the facility, the total number of deviation is 114, representing 3.2% of the total number of tags.

The deviations were analyzed using the process safety cumulative risk assessment logic/rule. The mapping of the impaired barriers using the functional location is shown in Figure 4 and the mapping of the impaired barriers on the major accident hazard bowties of the High Pressure gas compression Functional Location in the FPSO facility using the logic/rule set is presented in Figure 5.

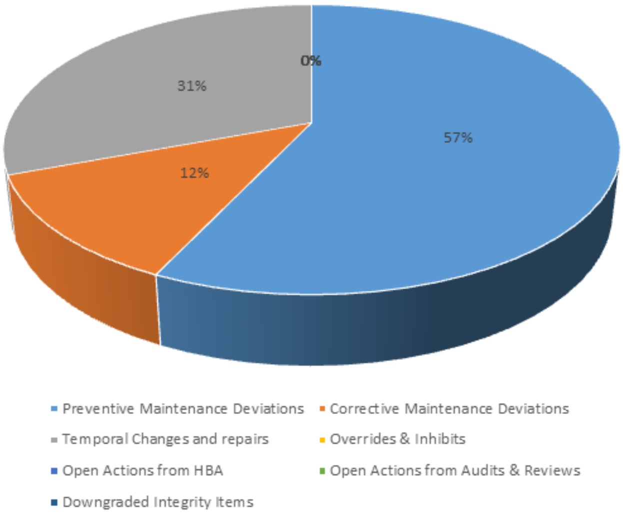

Figure 3. *Distribution of deviations in the FPSO Facility.*

	Preventive Maintenance Deviations (PMD)									Corrective Maintenance Deviations (CMD)									Temp Changes & Overrides/Inhibits (TCOI)								
	Structural Integrity	Process Containment	Ignition Control	Protection System	Detection System	Shutdown System	Emergency Response	Life Saving	**Total Nos - PMD**	Structural Integrity	Process Containment	Ignition Control	Protection System	Detection System	Shutdown System	Emergency Response	Life Saving	**Total No - EPAF**	Structural Integrity	Process Containment	Ignition Control	Protection System	Detection System	Shutdown System	Emergency Response	Life Saving	**Total Nos - TCOI**
Bilge & Ballast	2								2									0		1		2					3
Chemical Injection		5							5									0									0
Closed Drain		1							1									0									0
Fire & Gas					1				1									0					3				3
Flare		3	1						4									0		3							3
Flash Gas / VRU	1		1						2									0									0
Flowlines & Risers		3							3									0	2	5							7
Fuel Gas		2							2									0									0
Gas Dehydration		3							3									0									0
Gas Export		3							3									0		2				3			5
Heating Medium		1							1									0									0
HP Gas Compression		5							5									0		2							2
Power Distribution									0									0									0
HVAC			2						2									0									0
Inert Gas		1							1									0		2							2
Instrument Air		1							1									0									0
Interm Gas Comp		4							4									0									0
LP Gas Compression									0									0									0
LP Oil		2							2									0		2							2
Mooring	1								1									0									0
Oil Export		2							2									0		2							2
Oil Storage	1	8							9									0		1							1
Produced Water		3							3									0				1					1
Sea Water		1	1						2									0		6							6
Lighting																9		9									
Earthing													1					1									
Structural	2								2	3								3		1							1
Test Equipment		3							3									0									0
Wellhead		1							1									0				1					1
Diesel System															1			1									
No	7	52	5	0	1	0	0	0	65	3	0	0	1	0	0	9	0	14	2	27	0	4	3	3	0	0	39

Figure 4. *Mapping of impaired barriers by functional locations in the FPSO Facility.*

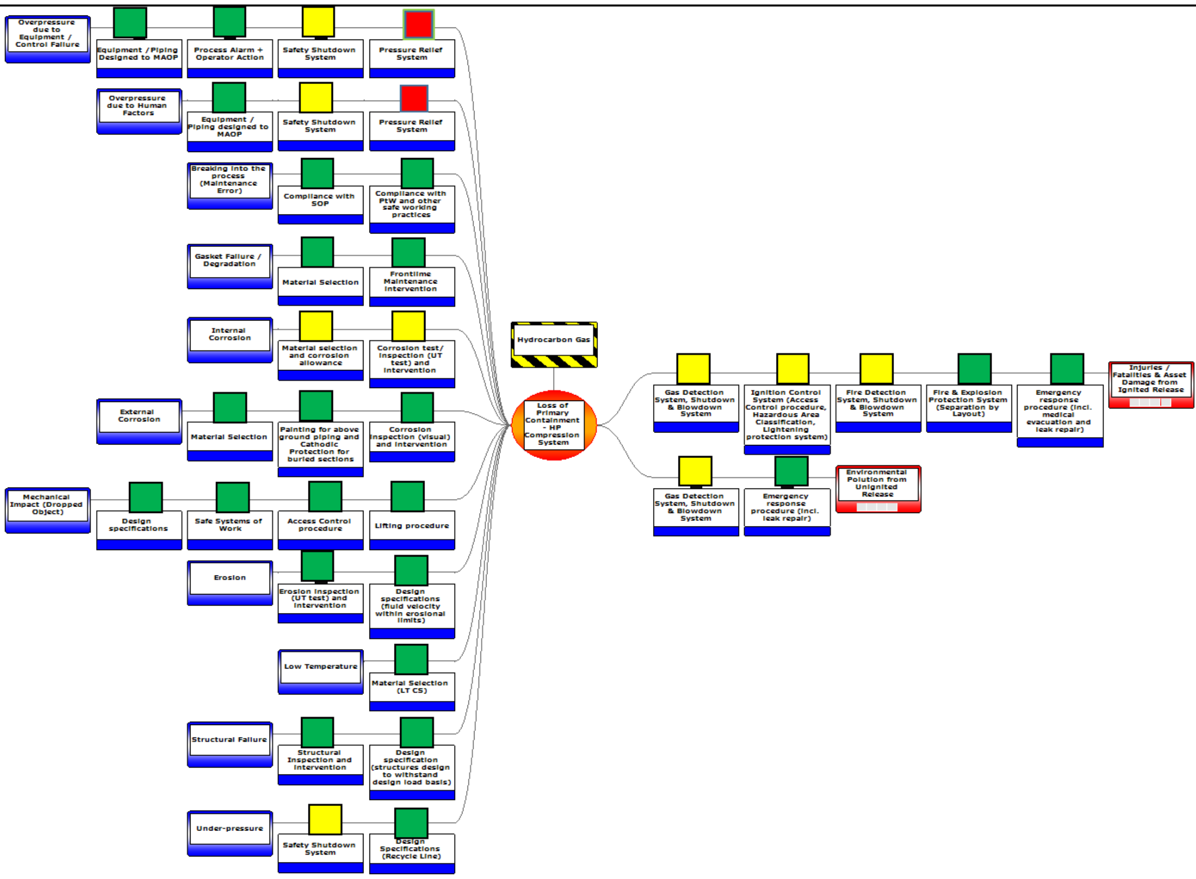

Figure 5. *Mapping of impaired barriers on major accident hazard bowtie of HP Gas Compression functional location in the FPSO Facility.*

Case Study 2 - Application on Gas Processing Facility Onshore Niger-Delta Nigeria

A site visit to the facility was conducted. At the time of the visit to the facility: 18 corrective maintenance deviations and 13 temporal changes/repairs and overrides/inhibits, one open action from hardware barrier assessment and one open action from safety review were identified. Figure 6 shows the distribution of the deviations in the gas plant facility. Out of the 1,995 tags in the facility, the total number of deviation is 33, representing 1.7% of the total number of tags.

These deviations were analyzed using the process safety cumulative risk assessment logic/rule set. The mapping of the impaired barriers using the functional location is shown in Figure 7 and the mapping of the impaired barriers on the major accident hazard bowties of the Gas Dehydration & Export Functional Location in the Onshore Gas Plant facility using the logic/rule set is presented in Figure 8. .

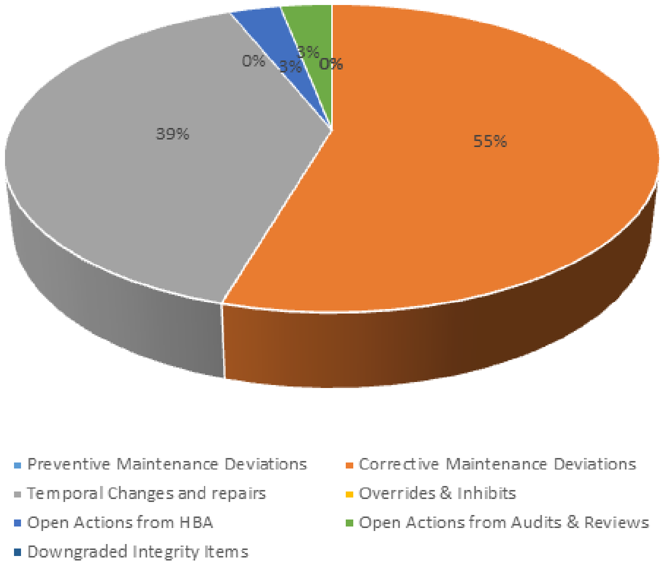

Figure 6. *Distribution of deviations in the Onshore Gas Plant Facility.*

	Preventive Maintenance Deviations (PMD)									Corrective Maintenance Deviations (CMD)									Temp Changes & Overrides/Inhibits (TCOI)								
	Structural Integrity	Process Containment	Ignition Control	Protection System	Detection System	Shutdown System	Emergency Response	Life Saving	**Total Nos - PMD**	Structural Integrity	Process Containment	Ignition Control	Protection System	Detection System	Shutdown System	Emergency Response	Life Saving	**Total No - EPAF**	Structural Integrity	Process Containment	Ignition Control	Protection System	Detection System	Shutdown System	Emergency Response	Life Saving	**Total Nos - TCOI**
Closed Drain									0									0									0
Fire & Gas									0									0									0
Flare									0									0									0
Flash Gas / VRU									0									0									0
Flowlines									0									0									0
Fuel Gas									0									0									0
Gas Dehydration & Export									0	1	1		1		1			4		1			2				3
Heating Medium									0									0									0
HP Gas Compression									0									0					3				3
Power Distribution									0									0									0
HVAC									0									0									0
Inert Gas									0									0									0
Instrument Air									0									0									0
LP Gas Compression									0		4			2				6					3				3
Condensate Storage/export											4	1		2				7		4							4
Lighting													1					1									0
Earthing																		0									0
Structural									0									0									0
Wellhead									0									0									0
No	0	0	0	0	0	0	0	0	0	1	9	1	2	4	1	0	0	18	0	5	0	0	8	0	0	0	13

Figure 7. *Mapping of impaired barriers by Functional Locations in the Onshore Gas Plant Facility.*

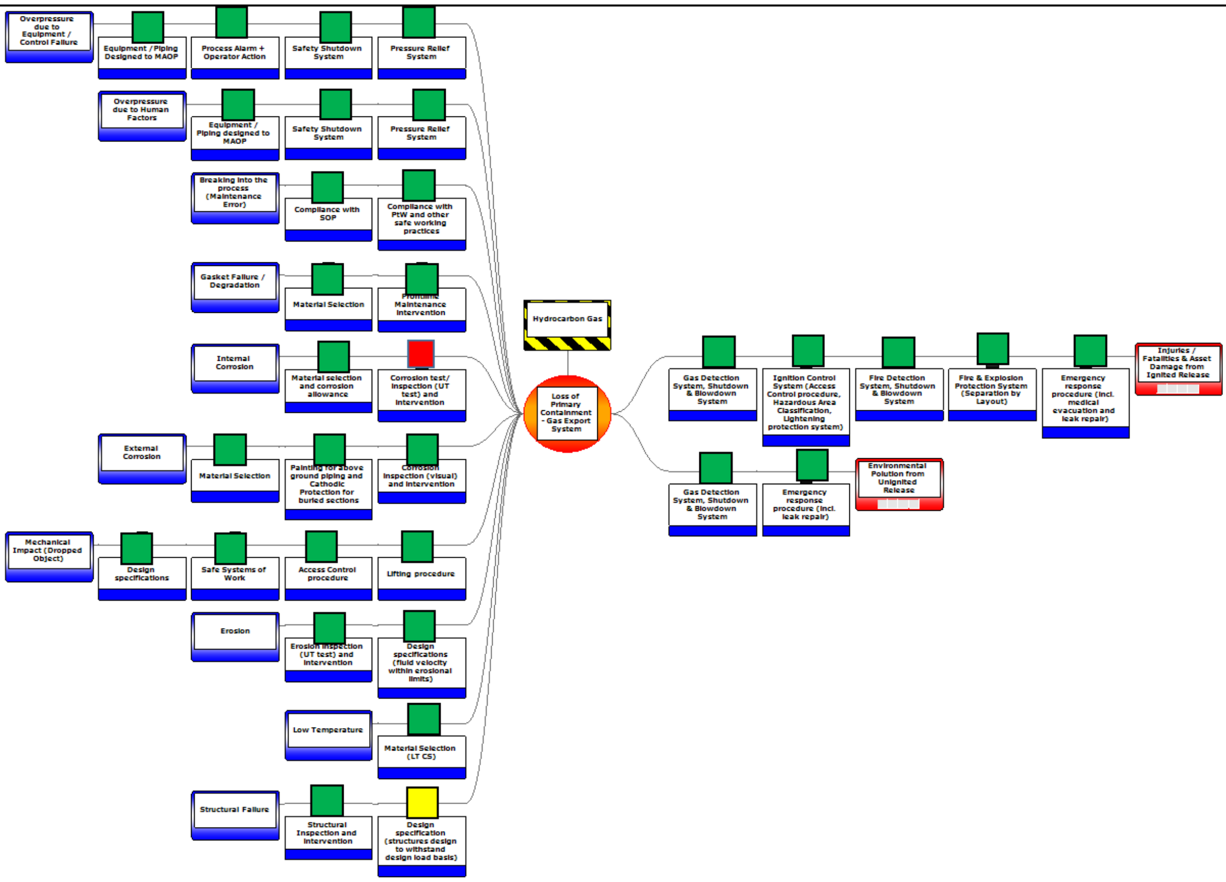

Figure 8. *Mapping of impaired barriers on major accident hazard bowtie of Gas Dehydration & Export Functional Location in the Onshore Gas Plant Facility.*

DISCUSSION

The process safety cumulative risk assessment logic/rule shown in Figure 1, highlights the "traffic light" risk scoring for impairment of safety critical barriers in an operating petroleum plant. This logic/rule was adjudged by the Focused number of people of process safety and asset integrity professionals as a very simple and practical way to assess risks arising from impaired safety critical barriers. The logic/rule is in line with the guidelines which recommended that scoring system should be on a list of safety critical barriers whereby the status of each barrier is indicated using 'traffic lights' format [30]. It is also consistent with the view expressed that "defined calculations" (referring to logic/rule) are to be used to perform computations on the extracted safety critical data to place the data in a form that can be presented to plant management, to eliminate variability in human interpretation of process safety risk levels [31]. The logic/rule also aligns with the approach on the design of the "barrier status panel" in Norway using the same "traffic light" format [25], even though the considerations for Green/Amber/Red scoring were a bit different.

The focused participants adduced that the model/framework in Figure 2 provides a clear guidance on process safety cumulative risk assessment and that the model literally covered every aspect of the process safety cumulative risk assessment related to safety critical barrier impairment. This observation addresses the concern that there is no consistent model or framework available for monitoring the health of barriers which is the necessary input into cumulative risk assessment [3]. The Focused participants observed that some petroleum facilities may have overwhelming number of deviations, making it very difficult and resource-intensive in collecting / filtering the data on the impaired barriers [25], given that the data is usually in disparate systems, lacking a single point of access. This agrees with the view that monitoring of overall asset integrity system of a production plant in a very objective and auditable way is challenging [5], further exacerbated by lack of centralized data repository on barrier impairment and human limitations to capture these data in an operating plants [32]. The participants also opined that due to the changing nature of these barrier impairment data due to various interventions in a facility in space and time, the risk picture is far from being static and is always in a state of flux. This finding is consistent with the view that barrier degradation is far from being simple and constant and requires constant vigilance to maintain functionality [21]. This also agrees with the view that there are many variables that affect barrier performance and these are ever changing [33]. The focused therefore recommended that some form of automation in data collection should be investigated, to obviate these problems and provide the risk picture on real time basis. This aligns with the view on the need for automation of data gathering and analysis for any model to be fit-for-purpose for process safety cumulative risk assessment [9].

On Case Study 1 (FPSO facility) and the results of the mapping of the status of the deviations (impairments) on the bowtie of the gas compression system of the FPSO facility shown in Figure 5, it is evident that there is risk accumulation on the gas compression facility functional location on three threat lines – overpressure due to equipment control failure, overpressure due to human factors and internal corrosion. This cumulative risk picture was not evident in the overall deviation summary for the gas compression facility picture shown in Figure 4, thereby reinforcing the value of the use of bowties to visualize risk accumulation.

For an example, on the threat of overpressure due to equipment failure on this system, there are 4 barriers on the major accident hazard bowtie of the facility - equipment design specification, process alarm and operator action, safety shutdown system and pressure relief system. Based on the process safety cumulative risk assessment logic/rule, equipment design specification barrier is healthy (Green), process safety alarm and operator action barrier is healthy (Green), safety shutdown system barrier is impaired (Amber) and pressure relief system barrier is greatly impaired (Red). On the threat of internal corrosion on this system, there are 2 barriers – material selection and corrosion allowance and corrosion inspection and testing. Of these barriers, material selection and corrosion allowance is impaired (Amber) based on the rule set/logic and corrosion inspection and testing is also impaired (Amber). On the recovery preparedness side (right hand side of the bowtie), there are 5 recovery preparedness barriers – gas detection system, ignition control system, fire detection system, fire and explosion protection system and emergency response, protecting against injuries/fatalities and asset damage. Of all these barriers, gas detection system and fire detection system are impaired (Yellow) based on the deviations in the system and according to the rule set/logic.

On Case Study 2 (Onshore Gas Plant) and the results of the mapping of the status of the deviations (impairments) on the gas dehydration & export facility on the onshore gas plant shown in Figure 8, it is also evident that there is accumulation of risk on the functional location. This cumulative risk picture was not evident in the overall deviation summary for the gas dehydration facility picture shown in Figure 7. For example, on the threat line of internal corrosion on this facility, there are 2 barriers – material selection and corrosion allowance and corrosion inspection and testing. Of these barriers, material selection /corrosion allowance barrier is healthy (Green) based on the rule set/logic and corrosion inspection and testing is highly impaired (Red). On the threat of structural failure on this system, there are 2 barriers – design specification and structural inspection / testing. Of these barriers, design specification is impaired (Amber) based on the rule set/logic and structural inspection and testing is healthy (Green).

The process safety cumulative risk assessment model/framework therefore represents a transparent and visible way of visualizing cumulative risk in a facility, for decision support in reducing major accident risk potential in daily operation of petroleum facilities. The model/framework will also help to eliminate variability in human interpretation of risk levels [31] and reduce reliance on expert opinion about risk levels in a facility. Due to the changing nature of the barrier impairments in time and space, the need for a web-based software for automation of barrier impairment data collection and real-time visualization of the cumulative risk picture was also established

CONCLUSIONS

The aim of this study was to develop process safety cumulative risk assessment framework/model for major accident prevention in petroleum operations in Niger-Delta Nigeria. Qualitative data was gathered and the data was analyzed using qualitative techniques. A focused number of people of process safety and asset integrity professionals were used to test the model/framework. Validating the model/framework was carried out in a workshop by the focused number of people using two case studies.

Through this exploratory study, a process safety cumulative risk logic/rule and process safety cumulative risk assessment model/framework were developed and validated. The results indicate that the process safety cumulative risk assessment framework/model offers a robust mechanism for providing visibility on process safety cumulative risks for improved operational decision making. When applied properly, the model/framework will help to reduce the risk of major accident in daily operations on petroleum facilities by:

1. Improving visibility of process safety risks across all areas of the operating facility
2. Facilitating management decision to deviate or extend the target due date of any of the process safety action item after taking the cumulative risk into consideration.
3. Having a clear visualization of "Gap to ALARP (As Low as Reasonably Practicable" for management of Major Accident Hazards and allows effective and better-informed risk-based decision making for:
   a) Deviation and deferral management
   b) Management of Change approvals
   c) Maintenance work prioritization

d) Override implementation
e) Simultaneous operations management

One improvement area identified in the model/framework is the need for a web-based software for automation of barrier impairment data collection and real-time visualization of the cumulative risk picture.

References

[1] Bhusari A, A. Goh, H. Ai, Sathanapally, S. Jalal, M and Mentzer, R (2020). “Process safety incidents across 14 industries. Proc Safety Prog. 2020; e12158. https://doi.org/10.1002/prs.12158

[2] Boogaerts G and Toeter, L. (2020). “Process safety education: Selecting the concepts for a process safety program” (article 1/2). Proc Safety Prog. 2020; e12186. https://doi.org/10.1002/prs.12186

[3] Behie, S. W., Halim, S. Z., Efaw, B., O’Connor, T. M., & Quddus, N. (2020). Guidance to improve the effectiveness of process safety management systems in operating facilities. Journal of Loss Prevention in the Process Industries, 68(June), 104257. https://doi.org/10.1016/j.jlp.2020.104257

[4] Ismail, Z. Kong, K. Othman, S. Law, K. Khoo, S. Ong, Z, and Shirazi, S (2014) “Evaluating accidents in the offshore drilling of petroleum: Regional picture and reducing impact,” Meas. J. Int. Meas. Confed., vol. 51, no. 1, pp. 18–33, 2014, https://doi.org/10.1016/j.measurement.2014.01.027

[5] Refsdal, I and Urdahl, O (2014). “Technical integrity management in Statoil,” Soc. Pet. Eng. - 30th Abu Dhabi Int. Pet. Exhib. Conf. ADIPEC 2014 Challenges Oppor. Next 30 Years, vol. 2, no. November, pp. 1456–1467, 2014, https://doi.org/10.2118/171813-ms

[6] Lee J, Cameron I, and Hassall M (2019). “Improving process safety: What roles for digitalization and industry 4.0?, Process Safety and Environmental Protection (2019), https://doi.org/10.1016/j.psep.2019.10.021

[7] Pawłowska, Z. (2015). “Using lagging and leading indicators for the evaluation of occupational safety and health performance in industry,” Int. J. Occup. Saf. Ergon., vol. 21, no. 3, pp. 284–290, 2015, https://doi.org/10.1080/10803548.2015.1081769

[8] Maduabuchi, E. Ugbebor, J and Oyet, G (2023c) “Analysis of critical risk factors in five iconic major accidents in petroleum and chemical operations. Journal of Scientific Research and Reports Volume 29, Issue 7, Page 57-70, 2023; Article no.JSRR.101097 ISSN: 2320-0227. https://doi.org/10.9734/jsrr/2023/v29i71760

[9] Jones, S. (2019). “Managing process safety in the age of digital transformation”. Chemical Engineering Transactions, 77(June), 619–624. https://doi.org/10.3303/CET1977104

[10] Tamim, N. Mentzer, R. Hasan, A. Mannan, M. (2016) “A Framework for Developing Leading Indicators for Offshore Drillwell Blowout Incidents. Process Safety and Environment Protection.

http://dx.doi.org/10.1016/j.psep.2017.01.005

[11] Neill, M. (2015). "Improving risk-based decision making by connecting PSM systems to day-to- day plant operations". AIChE National Spring Meeting, 11th Global Congress on Process Safety. 2015.

[12] Omidi, L. Dolatabad, K and Pilbeam, C (2022). "Differences in perception of the importance of process safety indicators between experts in Iran and the West". https://doi.org/10.1016/j.jsr.2022.11.002

[13] OGUK, "Cumulative Risk Guidelines," no. 1, pp. 1–34, 2016.

[14] Al-shanini, A., Ahmad, A., & Khan, F. (2014): Accident modelling and analysis in process industries. Journal of Loss Prevention in the Process Industries, 32, 319–334. https://doi.org/10.1016/j.jlp.2014.09.016

[15] Khakzad, N., Khan, F., & Amyotte, P. (2012). "Dynamic risk analysis using bow-tie approach". Reliability Engineering and System Safety, 104, 36–4 https://doi.org/10.1016/j.ress.2012.04.003

[16] Yang, X., & Haugen, S. (2015). Classification of risk to support decision-making in hazardous processes. Safety Science, 80, 115–126. https://doi.org/10.1016/j.ssci.2015.07.011

[17] Deng, Y., Sadiq, R., Jiang, W., & Tesfamariam, S. (2011). Risk analysis in a linguistic environment: A fuzzy evidential reasoning-based approach. Expert Systems with Applications, 38(12), 15438–15446. https://doi.org/10.1016/j.eswa.2011.06.018

[18] Andersen, S., & Mostue, B. A. (2012). Risk analysis and risk management approaches applied to the petroleum industry and their applicability to IO concepts. Safety Science, 50(10), 2010– 2019. https://doi.org/10.1016/j.ssci.2011.07.016

[19] Ishola, A. (2017). "Advanced Safety Methodology for Risk Management of petroleum refinery operations". A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy September 2017.

[20] Sarshar, S., & Haugen, S. (2018). Visualizing risk related information for work orders through the planning process of maintenance activities. Safety Science, 101(September 2017), 144–154. https://doi.org/10.1016/j.ssci.2017.09.001

[21] Pitblado, R., Fisher, M., Nelson, B., Fløtaker, H., Molazemi, K., & Stokke, A. (2016). Dynamic barrier management - Managing safety barrier degradation. Institution of Chemical Engineers Symposium Series, 2016-January (161), 1–8.

[22] Nwankwo, C D. (2020). Development of an Integrated Process Safety Management and Climate Change Model for the Oil and Gas Industry. https://pureportal.coventry.ac.uk/files/37907377

[23] Jonassen, Ø., & Sjølie, E. (2016). Barrier management in operation for the rig industry - A joint industry project. Offshore Technology Conference Asia 2016, OTCA 2016, 1980, 388–395.

https://doi.org/10.4043/26819-ms

[24] Haugen, S., Edwin, N. J., Vinnem, J. E., Brautaset, O., Nyheim, O. M., Zhu, T., & Tuft, V. L. (2016). Activity-based risk analysis for process plant operations. Institution of Chemical Engineers Symposium Series, 2016-January (161), 1–12.

[25] Nawaz, Z. and Jain, P. (2017). “Barrier Status Panel Tool for barrier management” 2nd International Conference on System Reliability and Safety 2017.