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PICA: Pipeline Integrated Corrosion Assessment Tool for Structure Integrity

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Abstract: The study develops an automated assessment tool specially tailored for corroding steel pipeline used to convey hydrocarbon deposit. The newly developed tool named PICA integrates deterministic and reliability method to evaluate the time-variant remaining allowable pressure of steel pipelines subjects to internal and external corrosion based on series of metal loss data. The deterministic assessment method is preferred by pipeline operator due to its simplicity, yet the accuracy is still arguable. The integrity of deterministic-based assessment results is dominantly governed by inherent uncertainties which are insufficiently covered by the introduction of safety factor. Whereas reliability assessment requires systematic data sampling and matching method as well as probabilistic nature of the parameters to give more credible and accurate result especially in estimating the corrosion growth rate. The combination of data sampling, statistical analysis, structure assessment and integrity prediction, a hybrid of deterministic and reliability-based methodology, has great potential to be developed as potent assessment software. The assessment software covers wide range of options including selection of assessment codes, corrosion models, data sampling techniques, assessment method and particularly effective to manage the vast amounts of collected data relating to pipeline condition, in a way that enables pipeline operators to monitor the pipeline integrity efficiently. By integrating various stages of pipeline assessment procedure into a systematic assessment framework, it can greatly assist pipeline operator to protect the public, financial investment and environment from such devastating effects owing to pipeline failures.

Key words: Pipeline, corrosion, integrity, probabilistic

INTRODUCTION

Corrosion is recognized as one of the most important degradation mechanisms that affect the long-term reliability and integrity of metallic pipelines (Li *et al*., 2009). Pipeline operators throughout the world are challenged with the expensive and risky task of operating aged pipelines because of corrosion and its potential damaging effects (Ahammed, 1998). Loss of the metal cross section is one of the major effects of corrosion and these results in a reduction of pipeline carrying capacity and safety and as the pipelines are ageing and corrosion may develop, the economical consequences of reduced operation pressure, repairs or replacements may become adversely high.

Assessment method is required to determine the severity of such defects when they are detected in pipelines (Cosham and Hopkins, 2003). The assessment condition of existing oil and gas pipeline is necessary in order to protect the public, financial. The assessment condition of existing oil and gas pipeline is necessary in order to protect the public, financial, investment and environment from such failures. Systematic and optimised regular inspections of pipelines with state-of-the art tools and procedures can reduce significantly the risk of any undue accident caused by a lack of unawareness of the integrity of the line (Cosham *et al*., 2007).

Pipeline corrosion assessment: As in-line inspection technology advances and tool resolution and accuracy increases, the traditional methods of dealing with In-Line Inspection (ILI) data are quickly becoming unfeasible, both from an economic and a practical point of view. Corrosion growth analysis provides a proactive method

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of analysing large quantities of ILI data, prioritizing pipeline repair programs and optimizing re-inspection intervals. It enables operator to fully understand the potential future risk to a pipeline due to corrosion (Desjardins, 2002). There is thus a need to provide the pipeline industry with an effective and affordable approach to assess corroding pipeline and in particular, a need to effectively manage the vast amounts of collected data relating to pipeline condition so that operators can maintain and prolong pipeline integrity. An initial review of pipeline integrity based on the operating history and the results of any past survey or inspections can potentially identify the likely problems and consequently the additional data that may needed to make a decision about the future of the pipeline (Jones and Hopkins, 2005). In order to achieve such optimization through full utilization of ILI data in structure maintenance scheme, the improvised of best practice assessment and prediction tools need to be developed.

Availability of assessment tools: The availability of pigging data in vast amount is just the first piece of solution towards pipeline sustainable and effective inspection, repair and maintenance scheme (IRM). The challenge is how to build a system capable of collecting data and turn it into information in the context of managing pipeline integrity (Wiegele *et al*., 2004). Recognizing the value of numerous of pigging data in industry, an inherent understanding of how to fully utilize pigging data for the sake of structure integrity assessment has become a necessity. A systematic approach to automate the assessment process by the means of software specially tailored to assess corroding pipeline with great capability of data processing and sampling as well as deterministic and reliability assessment engine is hardly available in the industry since existing tools are rather not comprehensive (Dawson *et al*., 2001).

In general, a good number of the existing pipeline assessment methods are purely deterministic and lacking reliability element as well as data sampling tool, hence under utilises the inspection data for the estimation of the variation of corrosion growth rate (Li *et al*., 2009; Melchers and Jeffrey, 2007). Available assessment tools for assessing corroding pipeline in industry such as Electronic Corrosion Engineer (ECE), ENCIPDA and CORROLINE is designed for internal pipeline and heavily rely on material and operation properties such as temperature, liquid flow velocity, hydraulic diameter of the pipe and others (Kvernvold *et al*., 1992). All the above mentioned parameters if not measured correctly on site can mislead the calculation of pipe remaining strength. While existing software such as RSTRENG used for determining the remaining strength of externally corroded pipe normally take into account of maximum depth of defect from the numerous number of inspection data merely (Bjornoy and Marley, 2001). Hence, neglecting the effect of defect variation upon pipeline failure probability.

The assessment procedure frameworks: The mainframe of PICA consists of four independent stages namely data sampling, data analysis and pipeline assessment and integrity prediction. Every single stage is developed as a standalone component with specific output. Even so, all stages are later integrated to give a comprehensive

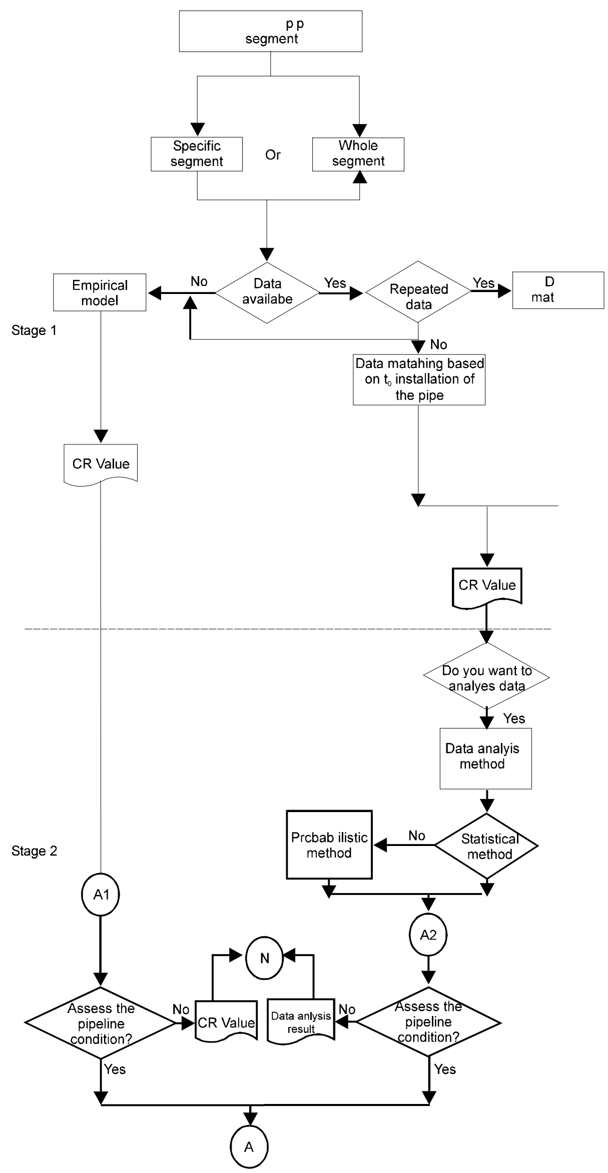

Fig. 1: Flowchart of data sampling and data analysis stages

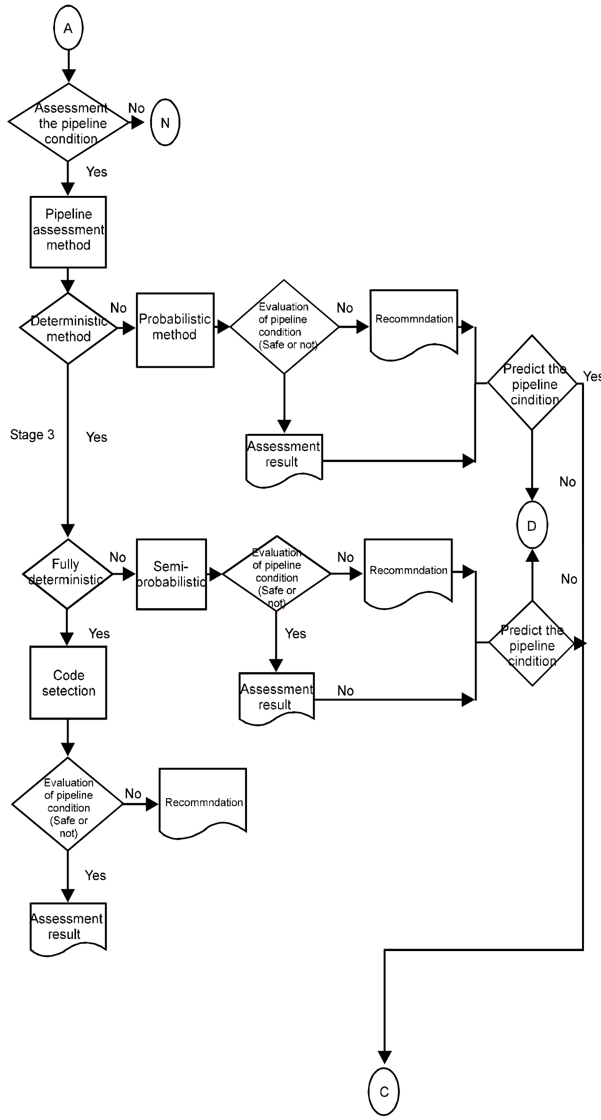

Fig. 2: Flowchart of pipeline assessment stage

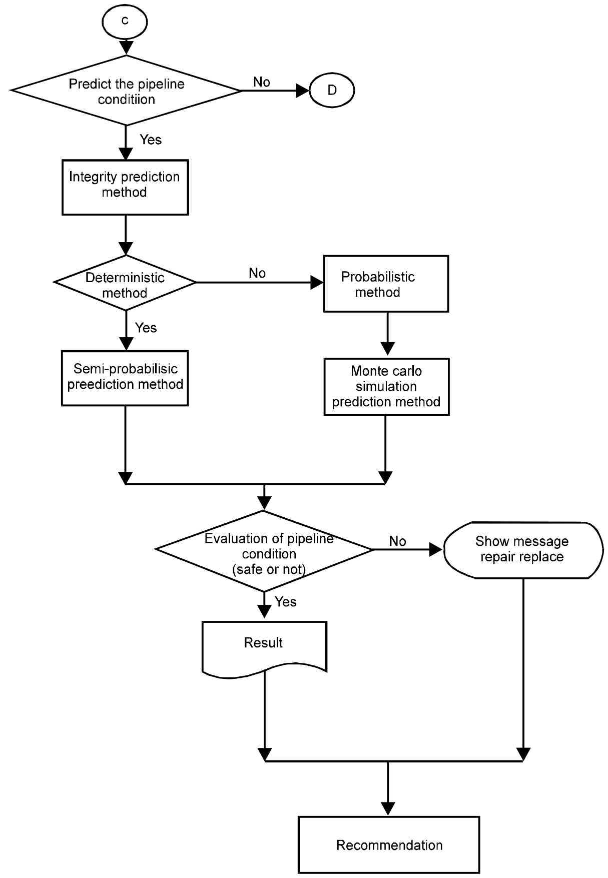

Fig. 3: Flowchart of integrity prediction stage

assessment option to pipeline owner if failure probability of the line becomes the preferable main output. Figure 1 to 3 depict the architecture of software. Data sampling and data analysis require large volume of inspection data which in practiced are often underutilised due to lack of understanding in handling the data statistically. Key to the effectiveness of PICA is the ability to assess with a measurable level of confidence, the corrosion rates for all defects on the pipeline. When multiple in-line inspections are available, corrosion rate determination is enhanced by software that automatically correlates defects from one inspection to the next. The appropriate level of confidence in growth rates and corrosion severity predictions is obtained by incorporating the error associated with inspection tools into all observations and subsequent calculations. The data optimisation can be used effectively to assess the integrity of the corroding pipeline so as to determine the level of fitness-for-service. The structure integrity assessment and prediction can be based on either deterministic or reliability method or combination of both.

Data sampling: In this study, historical data representing metal loss dimension (depth and length) measured through repeated pigging inspection are utilised to determine the corrosion growth rate. The calculation of growth rate is based on linear model. The sampling process is intended to match corresponding inspection data from previous inspection with the later one. When two or more inspections database available, individual defect growth rates can be determined with a decent degree of confidence. Corrosion rates are then calculated from the change in defect size between two or more inspections.

Determining the change in size however, presents the significant challenge of matching every defect from

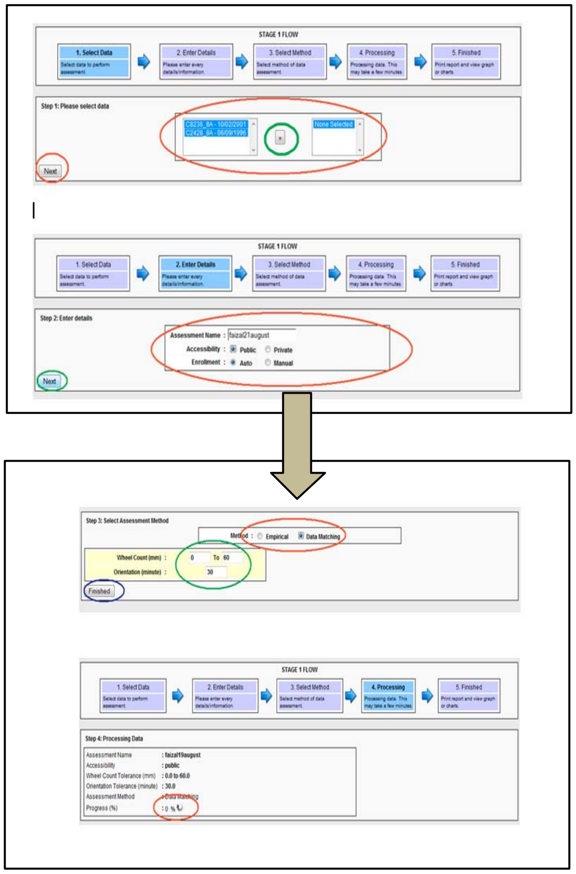

Fig. 4: Interfaces of data matching

multiple ILI data sets. Manual checks are conducted throughout the process to ensure data accuracy. This process takes full advantage of the ILI data and gather corrosion growth information, enabling the future repair and re-inspection needs to be assessed based on economy and safety issues (Dawson and Walker, 2005). The flowchart of data sampling procedure and its software interface are dipict in Fig. 4.

On the other hand, an empirical model of the deWaard and Milliams is included in the framework to give an option to the user when no repeated data available for the estimation of corrosion growth rate based on metal loss (Nyborg, 2006). The aforementioned model capable of estimating the averaged growth rate of internal corrosion by just relying on operational and flow parameters.

Data analysis: Data analysis provides useful information pertaining to corrosion mechanism such as defect dimensions and defect growth rate based on successful matched data. This process consists of two stages which are statistical and probabilistic analysis. Statistical method

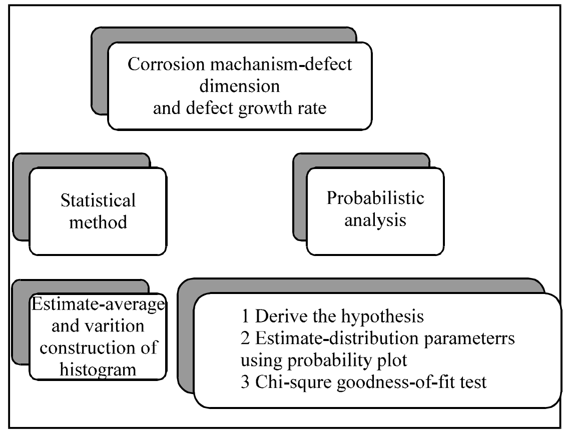

Fig. 5: Data analysis procedure

is used to estimate the average and variation of the corrosion parameters. Throughout several systematic probability methods, a proper distribution can be verified. The whole procedure is summarized in Fig. 5.

Under deterministic approach, histogram of the corrosion-related parameter is more than sufficient to provide vital information for calculating the remaining pressure of corroding pipeline. However, if the operator tends to use reliability method in the assessment process, it is requisite to enhance data analysis so as to cover the proper steps of probabilistic technique. Data analysis can be effectively used to locate data problem areas, measure data changing over time and increase the overall understanding of complex statistics. The information obtained from such analysis can have a significant effect on decision making.

Pipeline assessment: The evaluation of remaining strength and reliability assessment of corroded pipelines can be carried out using both deterministic and reliability methods. Deterministic assessment is a straight-forward approach based on codes or established capacity equation such as the ASME B31G, modified ASME B31G and DNV RP-F101 (Table 1). The failure pressure equation adopted in these codes is used to estimate the maximum allowable pressure for corroded pipeline. The available assessment codes can be categorised into two categories namely fully deterministic code and semi-probabilistic code. Fully deterministic code such as B31G equation does not cater the variation of the corrosion parameters as it is already represented by safety factor, hence poor capability of projecting the future remaining life of the pipeline. DNV (2004) has introduced a deterministic capacity equation with partial safety factors through its new assessment code known as RP-F101. The

Table 1: Capacity equation of pipeline remaining pressure

Methods	Equation	Remarks
ASME B31G 1991	$P_p = \frac{2\times S_f\times t\times F}{D}\left[\frac{1-\frac{A}{A_0}}{1-\frac{A}{A_0 M}}\right]$ A_o = original cross-sectional area of pipe at the defect A = area of the defect in the longitudinal plane through the wall thickness M = Folias bulging factor accounting for length and the projected shape of the corrosion	-ASME B31G Criterion [B31G, 1991]
DNV RP-F101	$P_p = \frac{\gamma_m\times 2\times t\times SMTS\times(1-\gamma_d(d/t)^*)}{(D-t)(1-\gamma_d(d/t)^*Q^{-1}}$ D = outer diameter d = depth of corrosion defect T = nominal pipe wall thickness L = measured length of corrosion defect $[d/t]_{meas}$ = measured relative corrosion depth γ_m = partial safety factor for prediction model and safety class γ_d = partial safety factor for corrosion depth ϵ_d = factor for defining a fractile value for corrosion depth SMTS = specified minimum tensile strength	

partial safety factor was developed with more advance probabilistic technique to improve the representation of uncertainties associated with defect dimension, hence the term semi-probabilistic.

The traditional design code which focused in deterministic methods are unable to predict the failure probability of corroded pipelines at given time and reference back to design code or specifications is likely to produce unduly conservative assessment (Li *et al*., 2009). As an alternative, the methods require a reliability engineering technique to assess future risk based on calculating the Probability Of Failure (POF). This method is based on the principle of load-resistance interference distribution. It has great capability of taking into account inherent uncertainties that govern the variation of corrosion parameters in order to improve the accuracy of pipeline assessment. As. previously mentioned, the outcome of this approach is the failure probability estimated using limit state function derived from pipeline capacity equation from the assessment codes.

Integrity prediction: The concept of integrity or reliability means that any attempt to quantify it must involve the use of statistical and probabilistic methods. Therefore to evaluate the future remaining life of corroding pipelines,

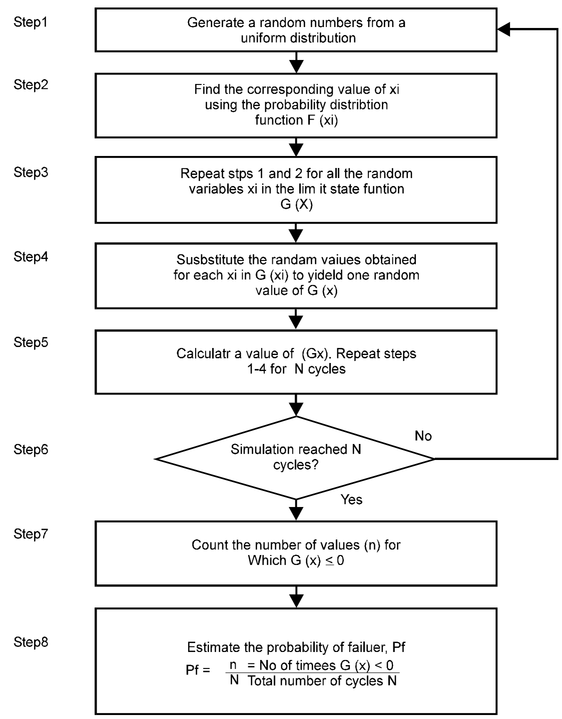

Fig. 6: Procedure of probability of failure estimation using monte carlo simulation method

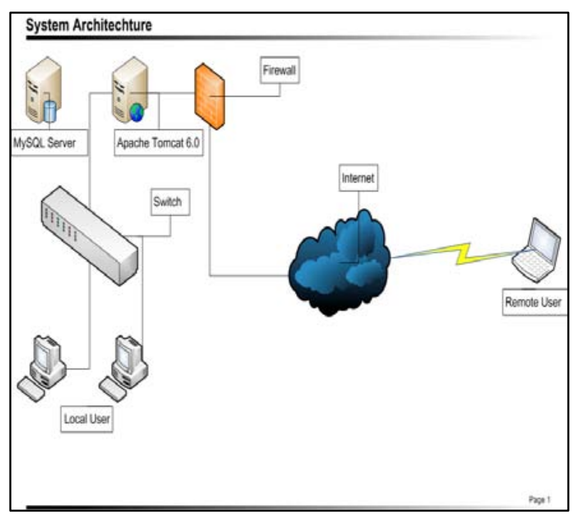

Fig. 7: System architecture

the use of statistical and probabilistic approaches are necessary. Since the outcome of the pipeline assessment based on reliability approach is the Probability Of Failure (POF), the load-resistance interference principle must be adopted.

Monte Carlo simulation is one of the methods for iteratively evaluating a deterministic model using sets of random numbers as inputs. This method is often used when the model is complex, nonlinear, or involves more than just a couple uncertain parameters. The variation in failure probability can be plotted against time and compared with the target probabilities for the limit state considered, the critical hazard and the time of pipeline failure can be identified. Monte Carlo simulation is preferable since this technique is less complicated and it can simulate a large number of experiments and the variables can be in any type of distribution.

This technique involves sampling of random variables from respective distribution and evaluating the numbers of failure attempt (violation of limit state function) over the number of simulation cycles, N. Limit state function shows how the pipeline fails (leakage or bursting). It is repeated many times with a new random vector of variables (Fig. 6). Therefore for N trials, the probability of failure is determined as;

$$P_f = \frac{n(G(x)<0)}{N} \quad (1)$$

n [G[x]<0 = number of trials which violated limit state function
N = number of trials.
P_f = probability of failure

Requirement and development of software system: The next stage is to integrate all of the standalone stages and later automate the assessment process using IT tools

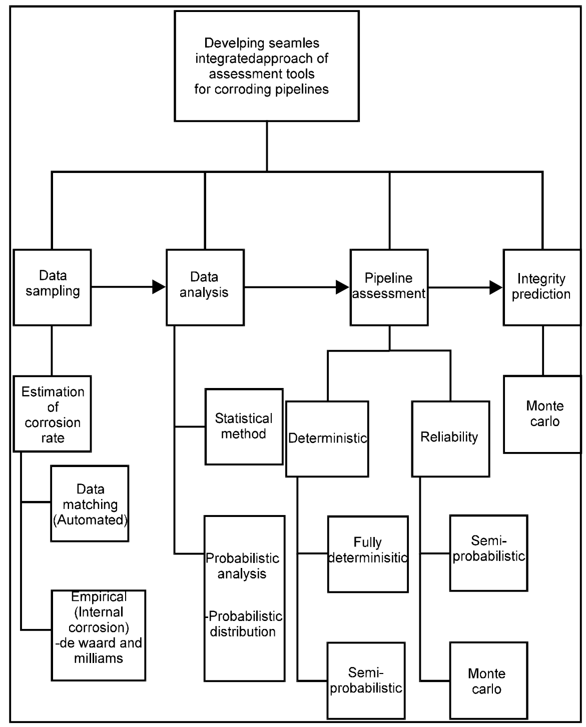

Fig. 8: Integration of assessment stages

Table 2: Types if programming platform and system utiliez in software development

Programming/System	Criteria
Java programming language	Java is well-known for its portability and the code can be run either on UNIX-based or Windows-based system. Java is widely used in scientific and engineering application nowadays. Alternatively, dot.Net framework is available but only compatible with Windows-based system.
Web-based approach	By using web-based platform, user can access to the system without any need for specific installation in their personal computer. Alternatively, developer can use stand alone application which needs to be installed beforehand.
Apache tomcat 6.0	Apache is an open source software provider and its main product is Apache Web Server. There are several versions of Apache and in this system, Apache Tomcat 6.0 was chosen for installation on UNIX-based machine or Windows-based machine.
MySQL 5.1	MySQL is a database tool with its main function to store system data. MySQL is open source software and can be installed on either UNIX-based machine or Windows-based machine. MySQL 5 support features like PL/SQL and Views.
Netbeans IDE 6.5	Netbeans IDE is open source software which focuses on Java technology and widely used by Java developer. Netbeans can be used to develop web-based software or standalone software. Plus, Netbeans can support native language like C++ and other programming language such as Ruby and PHP.
Adobe dream weaver CS3	Adobe Dream weaver is a development tool for web with a very user-friendly interface. Adobe Dream weaver is widely used to develop web interface and code whereby it can support many programming language such as Java JSP, PHP and ASP.
SQLYog 8.14	SQLYog is database editor software focused on MySQL database. SQLYog is a shareware and it's free edition only limited to certain features. Alternatively, Navicat can be used to replace SQLYog.
Amcharts	Amcharts is a flash-based application used to provide graphical data representation for this system. Amchart can be deployed on web-based application or standalone application and completely platform independent. Jchart can be used as an alternative to Amcharts with similar capability.

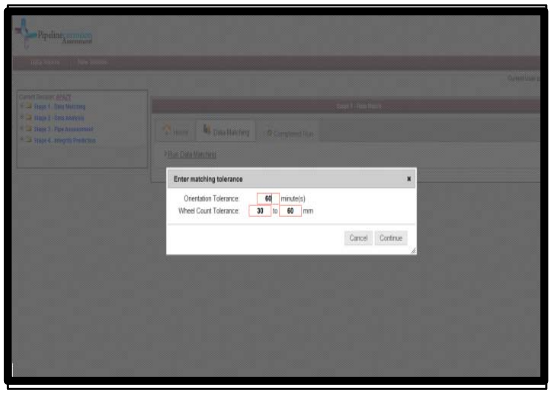

Fig. 9: Tolerance of orientation and wheel count for data matching in stage 1

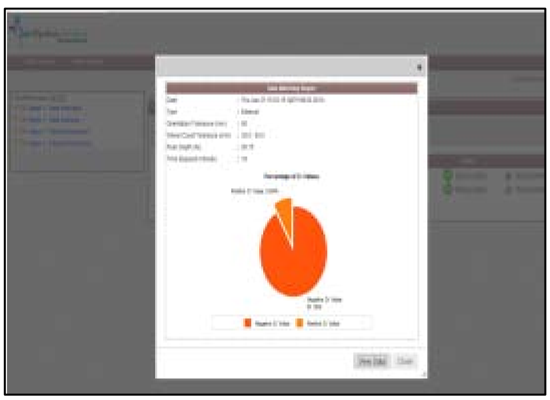

Fig. 10: Example of result from data matching in percentage

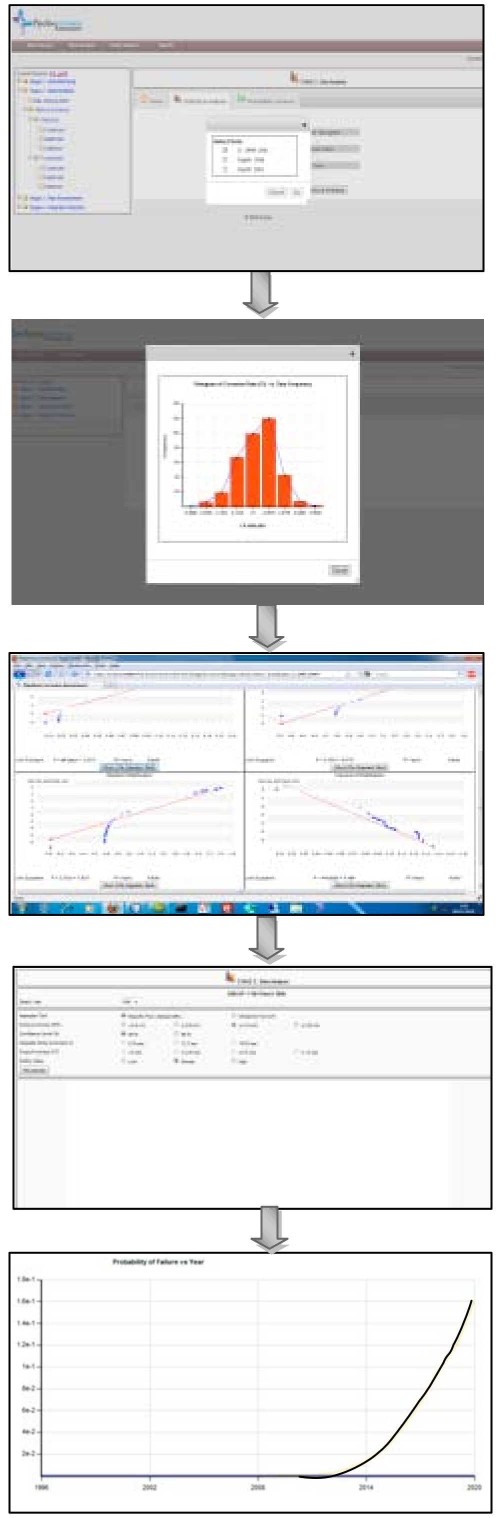

Fig. 11: PICA intrface of pipeline assessment

(Table 2, Fig. 7). The automation of the procedure is meant to boost the effectiveness and speed of the assessment and make it more marketable.

Integration of the assessment tools: The integration of four standalone stages as formerly mentioned in section IV: Methodology can assist pipeline operator to assess their assets integrity effectively at a much cheaper cost. Assessing structure integrity, pipeline in this case, involves multiple levels that requires combination of multi-dimensional knowledge covering variety of disciplines. As such, the overall assessment process becomes complex and impractical unless these multiple levels of assessment methodology can be integrated seamlessly.

The proposed assessment procedure meet adverse challenge to combine four standalone stages of data sampling, data analysis, structure assessment and integrity prediction under one single framework with flexibility of producing different types of output according to the selected stages. For instance, the user can choose to assess the pipeline remaining life at the time of inspection rather than projecting to the point where the structure might fail in the future. This selection only involves data sampling, data analysis and pipeline assessment without having to go through integrity prediction stage. Every single stage is designed to produce its intended output independently, yet the output can be utilized in other stage to achieve better output. In a simple word, the stages as mentioned in Fig. 8 are independent of each other unless the user decides to run multiple analyses under several stages.

Software demonstration: Data sampling procedure was conducted to match corresponding inspection results from different years manually in Stage 1. To locate the corresponding defects, information of girth weld, wheel count, and defect orientation is referred to. The existence of distance-related errors may cause difficulties in locating the pair of defect based on wheel count distance between two databases of pigging data (Fig. 9). Therefore, a reasonable margin of error /tolerance in regard to relative distance was allowed until sufficient numbers of data can be successfully matched to produce a proper distribution. Margin of errors/tolerance will alleviate difficulties in finding correct pair of data between two historical databases of pigging data. Figure 10 illustrates example of result from data matching in percentage. Result from data matching is then stored and ready for access in next stage to calculate probability of failure of the pipeline. Figure 11 shows the flow of the procedure in assessing the pipeline using this tool. The outcome from this procedure is a probability of failure either at the time of inspection or in the future.

CONCLUSION

The study will contribute to a betterment of pipeline integrity assessment as presently practiced by pipeline operators. It will encourage pipeline operators to optimise the large volume of inspection data gained through precipitous-cost pigging inspection for assessment purposes. The integration of different processes related to pipeline assessment is hardly feasible due to the complexity of reliability method and the issue on the availability of pipeline inspection data.

By integrating two different principles of deterministic and reliability engineering to form a comprehensive assessment package, pipeline operators can have a great option to choose either deterministic or reliability approaches according to the targeted requirement. Moreover, the proposed seamless integrated approach as a software package may simplify yet maintain the practicality aspect of pipeline fitness-for-service evaluation, hence minimise the future maintenance cost that may arises due to structure failure associated with corrosion defects.

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