Institution: Brunel University London		
Unit of Assessment: 10 - Mathematical Sciences		
Title of case study: Risk-based integrity management systems for steam systems and pipelines based on quantile regression models		
Period when the underpinning research was undertaken: 2016-2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Keming Yu	**Role(s) (e.g. job title):** Professor	**Period(s) employed by submitting HEI:** 2005-present
Period when the claimed impact occurred: 2017-December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Prof Yu's research on the application of various regression models has been fully incorporated into 2 commercial software packages, *Steam System Reliability Management (SSRM)* and *RiskWISE* to manage the structural integrity of steam systems and pipelines since 2017. Both packages have been developed by and support the ongoing activities of The Welding Institute (TWI). [text removed for publication] *RiskWISE* is a risk-based management system which enables plant personnel to identify plant and equipment at risk of failure and allocate inspection and management resources optimally to mitigate risk in a safe and cost-efficient way; this helps assess the remaining useful life of assets such as offshore oil and gas wellhead conductors. This has informed TWI's input to the development of the American Petroleum Institute's risk-based inspection technology 581 standards (API RP 581), thereby providing benefits to wider stakeholders in industry. *RiskWISE* is currently licensed to over 100 companies worldwide including an international oil and gas conglomerate that holds one of the 10th largest oil reserves in the world.

2. Underpinning research (indicative maximum 500 words)

Brunel University London has a long-standing strategic relationship with The Welding Institute (TWI). Prof Yu from Brunel has been working collaboratively with TWI to develop an algorithm which can accurately predict corrosion, crack size and the remaining life of a pipeline since 2016.

Buried pipelines are normally protected with a cathodic protection (CP) system and monitoring of the CP system, the coating and the overall integrity of the pipeline are normally addressed by conducting an external corrosion direct assessment (ECDA). This process includes an indirect assessment as well as the direct current voltage gradient (DCVG), which is used to identify the location of coating defects and to classify their severity. Based on a defect's severity, a decision can be made on whether to proceed with further direct assessment which requires excavation of the defect location. The DCVG technique can accurately determine a defect location but lacks the accuracy in predicting the defect size (area).

Prof Yu's research developed a new methodology for using quantile regression models to define the relationship between areas with coating breakdown, corrosion DCVG measurements and factors capturing various environmental conditions. This research was based on the empirical data collected from over 300km of crude oil pipeline with excavations carried out at 200 locations. His analyses confirm that DCVG cannot be used alone as an inspection technique to locate coating defects to predict the size of coating defects with high confidence. The voltage drop (%IR) is an indicator of coating defect size but does not show correlations with corrosion

depths, thus using this could be misleading in an integrity assessment to identify sections potentially less (and more) susceptible to failure. As the corrosion depth is not necessarily proportional to coating defect size, both small and large coating anomalies for cathodically unprotected pipelines should be considered in analyses. The research showed that applying multiple regression models, taking into account environmental and other factors, provides more accurate predictions. [Ref 1]

Prof Yu's algorithm models the relationship between the coating defect area and its possible dependent variables. Using quantile regression to fully characterise the dependent variable, the research was conducted based on the empirical data which included the design data of the pipes of the Middle Eastern Oil Company – design philosophy, material selection, physical characteristics of the pipe – and historical operation data. The results from the indirect and direct assessment part of the ECDA were modelled using the classical quantile regression and the Bayesian quantile regression methods to investigate the effect of factors toward the IR drop (%IR) and the coating defect size.

Prof Yu's research proved that the Bayesian quantile regression can include all parameter uncertainty, which makes it an essential tool for engineers in assessing uncertain data. ECDA pipeline data for DCVG technique in particular incorporates large amounts of uncertainty – such as soil component and human factors – and Bayesian techniques allow the quantification of the full spectrum of uncertainty in for the predicted parameters. [Ref 2]

Prof Yu's research has led to the development of a risk-based integrity management approach to pipelines and steam systems.

3. References to the research (indicative maximum of six references)

[Ref 1] Anes-Arteche F., Yu K., Bharadwaj U., Lee C. and Wang B. Challenges in the application of DCVG-survey to predict coating defect size on pipelines. *Materials and Corrosion* 2017: 329-337. https://doi.org/10.1002/maco.201608917

[Ref 2] Bin Muhd Noor NN, Yu K, Bharadwaj U, Gan T-H. Making use of external corrosion defect assessment (ECDA) data to predict DCVG %IR drop and coating defect area. *Materials and Corrosion*. 2018: 1–20. https://doi.org/10.1002/maco.201810085

4. Details of the impact (indicative maximum 750 words)

Pipeline corrosion can occur as early as one year after a pipeline system is in operation and its damage can threaten its structural integrity, leading to devastating results in residential, commercial or industrial sites. Buried pipelines are coated with a protective layer which will deteriorate depending on multiple factors and estimating its extent of corrosion is key for managing steam, gas and oil pipelines.

The Welding Institute (TWI) has incorporated Prof Yu's research in 2 commercial software packages – *Steam System Reliability Management (SSRM)* and *RiskWISE* – to manage the structural integrity of steam systems and pipelines respectively in 2017. Both are risk-based management systems whose algorithms enable accurate assessment of pipe conditions, whether predicting a size of crack or the extent of corrosion, to estimate the lifespan of pipelines accurately.

Economic benefits

SSRM has been used by TWI's clients in managing the structural integrity of their steam systems and this has generated substantial income for TWI since its use in 2017. [text removed for publication] Due to its high applicability and accuracy of the system, TWI has seen its increasing use internationally and reported that this has been deployed in Japan, Mexicoand UAE. [E2]

RiskWISE enables their clients to assess the remaining useful life of their offshore oil and gas wellhead conductors. [text removed for publication]

Changing the Standard for mitigating risks in a safe and cost-efficient way

Both SSRM and RiskWISE play a significant role in assessing pipelines' future life extension decisions and allow companies to make more efficient use of maintenance resources. Using the algorithm in this way helps operators understand the fitness for service of the conductors and estimate their future corrosion levels and remaining useful life. This is particularly important for the safety of plant personnel as the company would allocate inspection and management resources based on the assessment of plant and equipment at risk of failure.

In other words, companies can have more targeted scheduling of inspection and maintenance work while 'improving safety, facilitating increased run times and reducing expensive outage costs' [E2]. This has led TWI to develop a bespoke software for a Malaysian industrial partner, which allowed the more accurate monitoring of underground storage tanks, leading to a reduction in reactive shutdowns and increased safety. [E2]

Work on steam systems has informed TWI's input to the development of the American Petroleum Institute's risk-based inspection technology 581 standards (API RP 581), thereby providing benefits to wider stakeholders in industry. [E3]

5. Sources to corroborate the impact (indicative maximum of 10 references)

E1) Private communication – Corroborator information provided.

E2) Corroborating letter from TWI Ltd.

E3) RiskWISE ® for Pipelines Brochure from TWI Software:

http://www.twisoftware.com/software/integrity-management-software/riskwise-for-pipelines/