Institution: University of Kent

Unit of Assessment: 10: Mathematical Sciences

Title of case study: Statistical Modelling Provides Economic Benefits to Manufacturers of Process Instrumentation

Period when the underpinning research was undertaken: 2011-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr Xue Wang	Senior Lecturer in Statistics	2007-present
Prof. Stephen G. Walker	Professor in Statistics	2004-2013

Period when the claimed impact occurred: 2014-2020

Is this case study continued from a case study submitted in 2014? Yes

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

The research presented in this case study contributed to the growth in turnover of KROHNE Ltd from £37m in 2014 to £53m in 2019. This was achieved through two Knowledge Transfer Partnerships that addressed real-world problems of flow metering in industrial processes and improved the company's core product, the Coriolis flowmeter. The collaboration with KROHNE also enabled the company to develop new products and led to an improved organisation of their Research and Development Team, thereby increasing cost efficiency. Furthermore, the research presented in this case study contributed to innovation and entrepreneurial activity in China through the creation of a CO_2 flow rig, which is being used as a test facility by companies, including Walsn, who are seeking to increase coal-burning efficiency.

2. Underpinning research (indicative maximum 500 words)

The research that underpins the impact is twofold, involving improved regression models and soft computing techniques.

Strand 1: Regression models for single phase conditions

Traditionally, industrial practices adopted ordinary least squares (OLS) regression models to estimate the cause-and-effect relationships. For our industrial partner, KROHNE, which relies on calibration procedures to produce precision measuring instruments, an OLS regression model was used to calibrate the Coriolis flowmeters under varying environmental conditions such as temperature and pressure. This model requires a large number of measurements per device to achieve accuracy, which proved costly in terms of material, time, and human resource. Meanwhile a large amount of available historical data had not been exploited to improve efficiency of the calibration process. Research funded by **G1** made it possible for this historical data to be utilised and led to the development of a new Bayesian nonparametric model, which is capable of estimating an unknown function in the presence of Gaussian noise **[R1]**.

The proposed new model involves a mixture of a point mass and an arbitrary (nonparametric) symmetric and unimodal distribution for modelling wavelet coefficients. It provides a natural framework for incorporating historical data through the introduction of a prior distribution. Using Bayesian ideas, Eves (RA funded through the grant **G1**), Wang, and Walker in 2014 further developed a novel theory for linear regression models and showed how the reduction in individual sensor measurements could be achieved **[R2]**. Consequently, Wang fitted the new model to

historical data collected from similar sensors tested by KROHNE. It was found, however, that the multimodality and skewness exhibited in the historical data deteriorated the accuracy of calibration. To tackle these features of the data, Wang and Walker in 2017 proposed an infinite mixture model, with weights attached to a set of multivariate normal distributions, employing an optimal ordering scheme **[R3]**. This enhanced the flexibility of the model and overcame the inaccuracy problem caused by the distribution misspecification of the historical data.

Strand 2: Adding soft computing techniques for multiphase conditions

The new Bayesian nonparametric model worked well for single phase conditions (i.e. with either gas, liquid, or solid). However, large errors occurred under multiphase conditions (with gas and liquid, for example). After extensive experimental work conducted on a purpose-built two-phase flow test rig on both horizontal and vertical pipelines (funded through the grant **G2**), the detailed principles, structures, and performance comparisons of different models were produced in **R4**. It was shown that different models with the same data perform differently, and that different model parameters affect the performance of the data-driven models. This suggested that input variable selection methods should be carefully controlled. In **R5**, Wang and her co-authors thoroughly discussed the procedures of the input variable selection to eliminate irrelevant or redundant variables by identifying a suitable subset of variables. This simplified the model structure and increased computational efficiency. A further collaboration with KROHNE via grant **G3** made it possible for the results of **R5** to be applied to Coriolis flowmeters (one of KROHNE's core products) by developing two error-correction algorithms. Building on both theoretical knowledge and practical experience through collaborations, a review defining the state of the art in the development of multiphase flowmeters incorporating soft computing techniques, as well as their merits and limitations, was presented in **R6**.

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

[R1] Wang, Xue, Walker, Stephen G. (2013). 'Full Bayesian wavelet inference with a nonparametric prior'. *Journal of Statistical Planning and Inference* 143(1): 55-62. ISSN 0378-3758. doi: http://dx.doi.org/10.1016/j.jspi.2012.05.010

[R2] Eves, Christopher, Wang, Xue, and Walker, Stephen G. (2014). 'Bayesian Information for Sensors'. *Quality and Reliability Engineering International* 31(8): 1717-1724. ISSN 0748-8017. doi: http://dx.doi.org/10.1002/qre.1704

[R3] Wang, Xue, and Walker, Stephen G. (2017). 'An optimal data ordering scheme for Dirichlet process mixture models'. *Computational Statistics and Data Analysis* 112: 42-52. ISSN 0167-9473. doi: http://doi.org/10.1016/j.csda.2017.02.010

[R4] Wang, Lijuan, Liu, Jinyu, Yan, Yong, Wang, Xue, and Wang, Tao. (2017) 'Gas-liquid Two-phase Flow Measurement Using Coriolis Flowmeters Incorporating Artificial Neural Network, Support Vector Machine and Genetic Programming Algorithms'. *IEEE Transactions on Instrumentation and Measurement* 66(5): 852-868. ISSN 0018-9456. doi: https://dx.doi.org/10.1109/TIM.2016.2634630

[R5] Wang, Lijuan, Yan, Yong, Wang, Xue, and Wang, Tao. (2017). 'Input variable selection for data-driven models of Coriolis flowmeters for two-phase flow measurement'. *Measurement Science and Technology* 28. 035305. ISSN 0957-0233. doi: https://doi.org/10.1088/1361-6501/aa57d6

[R6] Yan, Yong, Wang, Lijuan, Wang, Tao, Wang, Xue, Hu, Yonghui, and Duan, Quansheng (2018). 'Application of Soft Computing Techniques to Multiphase Flow Measurement: A Review'. *Flow Measurement and Instrumentation* 60: 30-43. ISSN 0955-5986. doi: https://dx.doi.org/10.1109/TIM.2016.2634630

Research grants

[G1] Wang, Xue (2011-13). Innovation UK (No KTP008285). 'Model-based regression methods for calibrating and verifying vibratory devices to measure flow and density'. Value: £124,776.

[G2] Yan, Yong, and Wang, Xue (2014-16). The UK Carbon Capture and Storage Research Centre (UKCCSRC-C2-C218). 'CO_2 flow metering through multi-modal sensing and statistical data fusion'. Value: £136,497.

[G3] Yan, Yong, and Wang, Xue (2018-20). Innovation UK (No KTP010905). 'Development of multiphase flow measurement technology through a soft computing approach'. Value: £169,772.

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

KROHNE: impact on commerce and the economy, production and improvements for the R&D team

The collaboration with KROHNE (resulting largely from the KTP project **[G1]**) has improved the business performance and contributed to KROHNE's growth in turnover from £37m in 2014 to over £53m in 2019 **[a, d]**. General Manager Edward Jukes stated that the 'specialist input and research expertise of the Kent team have been invaluable and have enhanced our competitiveness in precision instrumentation manufacturing' **[a]**. He explained that optimisations in product calibration procedures resulting from the first project **[G1]** have been 'embedded in every product since 2013 with great success. The Kent research team also discovered that we had measuring components that were not actually needed for the performance of some of our meters and potentially led to overfitting of equations. By removing these components, we have saved over £100k in component costs alone.' **[a]**.

Between 2018 and 2020, the company was able to employ 300 new members of staff **[b]** and filed a patent **[a]**. Jukes confirms that 'The KTP associate, Dr Jinyu Liu, joined KROHNE Ltd. as a full time R&D engineer after successful completion of the second project with KROHNE **[G3]** in March 2020. He brought with him much needed expertise [in statistical modelling and machine learning to develop KROHNE's products further]' **[a]**. In other words, the development of the two feasible solutions to use Coriolis flowmeters to measure gas-liquid flow resulting from the project **[G3]** established KROHNE's competitiveness. These solutions make it possible to enhance existing products and to bring new products to market, including in industries in which Coriolis flowmeters have had limited use so far due to inaccuracies. 'This includes the food & beverage, chemical, marine and oil & gas industries' **[b]**. The error-correlation algorithms, in turn, will enable KROHNE's current £10k core Coriolis products to match the performance of a £100k-150k flowmeter **[b]**. 'This statement was verified on one of our core products (OPTIMASS 2400 S100) for bunkering application during the KTP report and now it is also verified on another core products (OPTIMASS 6400 S50) for oil and gas applications' **[c]**. KROHNE aims to have a product based on this research in 2021 **[c]**.

The project **[G3]** also highlighted the need for a different management structure within KROHNE's R&D department to ensure more effective implementation of projects and better ring-fencing of research activities. '[The] restructuring started during the KTP and is already delivering improvements – for example, in project planning and reporting' **[b]**.

CO_2 flow rig: contributing to innovation and enterprise activity related to fuel efficiency

The completion of the CO_2 two-phase flow rig at North China Electric Power University in 2016 made it possible for numerous experiments on CO_2 at different conditions to be carried out, leading to publications in leading journals (see examples in **[e, f]**), networking opportunities, and the securing of external funding, including grants, from the UK and China **[e]**. Lijun Sun, Associate Professor at Tianjin University, commented: 'This test facility is unique since it allows the simulation of two-phase flow conditions as would be encountered in real CCS (carbon capture and storage) pipelines. This is important because two-phase CO_2 behaves very differently from its single-phase condition, which may even cause safety concerns' **[f]**. It is, however, not only

academic researchers across UK and China who have used the facility to test CO_2 leakage, flow measurement, and transient behaviours; the facility has also attracted attention from a leading CCS research organisation, NCCS (Norwegian CCS Research Centre), with Sintef as its project leader. In collaboration with KROHNE, NCCS made contact with the facility and explored how to use the rig to test fiscal metering **[f]**. Lijun Sun stated that 'Our innovations are benefiting from knowledge exchange and [are] likely to influence professional standards in the long run, not least given the ever-increasing demand to reduce greenhouse gas' **[f]**.

Walsn Energy Technology is one of the companies that has been using the test facility since 2019 to explore the possible application of statistical signal processing for a new project in a coal-fired plant. Technical Director Shoubing Chang considers increasing fuel efficiency and reducing pollution to be a key challenge **[g]** that the company is aiming to tackle. The accurate measuring of coal powders flowing in the pipe and using statistical signal processing to achieve this has become one of their core projects. Shoubing Chang credited the Kent team led by Dr Wang for contributing to the project through researching existing methods and introducing new ideas **[g]**. Now that preliminary results have shown 'promising outcomes' **[g]**, they are seeking a more formal collaboration.

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

[a] Letter from the from General Manager/Technical Director of KROHNE Ltd, corroborating the impacts that occurred in the eligible period from the Knowledge Transfer Partnership (KTP) projects **[G1** and **G3]**, both of which have been awarded the highest grade of 'outstanding'.

[b] KTP (No KTP010905) report, providing a summary of the KTP partnership **[G3]** (2018-2020).

[c] Email from the General Manager at KROHNE Ltd (18 December 2020), providing an update to the KTP report.

[d] Data from Companies House on KROHNE's financial turnover, 2014-19.

[e] Letter from a Professor of Thermal Energy Engineering at North China Electric Power University, confirming that the establishing of the CO_2 Flow Rig test facility is a result of the collaboration.

[f] Letter from Director of Tianjin University Flow Lab, on the use of the CO_2 Flow Rig test facility.

[g] Letter from the Technical Director, Walsn, on the use of the CO_2 Flow Rig test facility.