Section A

Institution: Durham University

Unit of Assessment: Mathematical Sciences UoA 10

Title of case study: Emulation and History Matching in the Oil and Gas Industry

Period when the underpinning research was undertaken: 2008-2016

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 Ian Vernon	Associate Professor Assistant Professor Research Fellow/Associate	April 2017 to date 2011 - 2017 2006 - 2010
Prof. Michael Goldstein	Professor	1990 - to date
Dr Jonathan Cumming	Assistant Professor Research Fellow/Associate	2015 to date 2006-2014

Period when the claimed impact occurred: 1st August 2013 to 31st December 2020

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

Section B

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

ENABLE is an emulation, history matching and uncertainty assessment software system for the oil industry, sold by Roxar/Emerson, whose inference engine was produced and subsequently improved by the Durham Statistics group, based on their research on uncertainty quantification for complex physical systems modelled by computer simulators. ENABLE optimizes oil asset management plans by careful uncertainty quantification and reduces development costs by accelerating the history matching process for oil reservoirs, resulting in vastly improved technical and economic decision-making. This led to substantial and sustained impact (a) for Roxar/Emerson as annual sales of ENABLE are approximately USD2,300,000, and (b) for their oil company clients, as ENABLE enjoys global usage by more than 16 major oil companies, including [redacted].

2. Underpinning research (indicative maximum 500 words)

The Durham Statistics Group has a long track record of work on the quantification of uncertainty for large and complex physical systems modelled by computer simulators. Example areas include climate, cosmology, epidemiology, systems biology and history matching for oil reservoirs, the subject of the current impact case study. This problem may be described as follows. Reservoir simulators are key tools to help oil companies manage production for oil reservoirs. The simulator takes as inputs a description of the reservoir (rock properties, fault distribution and so on) and returns as outputs the well performance (pressure profiles, production, water cut and so forth). As the appropriate input choices are not known a priori, the input space must be searched to identify choices of reservoir specification for which the output of the simulator at the wells corresponds, to an acceptable degree, to recorded historical behaviour. This process is termed history matching. It is difficult and challenging because the input and output spaces are high dimensional, the evaluation of the simulator for a single choice of inputs takes many hours, and there are multiple additional sources of uncertainty that must be included to make the analysis meaningful.

The Durham group devised a detailed Bayesian solution to this problem, based on building an emulator for the simulator. This is a probabilistic surrogate for the simulator, giving both a fast approximation to the simulator and a measure of uncertainty related to the quality of the approximation. This emulator, in combination with an uncertainty representation for the difference between the simulator and the reservoir, forms the basis of the history matching methodology that we developed. This proceeds by eliminating those parts of the input space for which emulated outputs were too far from the observed history, according to a collection of appropriate implausibility measures, then re-sampling and re-emulating the simulator within the reduced space, eliminating further parts of the input space and continuing in this fashion. This is a form of iterative global search aimed at finding all of the input regions containing good matches to the history.

Building on initial progress made in 1993-1997 which was the focus of a previous impact case study, the Durham statistics group have, since 2008, developed award winning (Mitchell Prize for Best Applied Bayesian journal article worldwide, 2010) advances to multiple components of the history matching process for general simulators **[R1].** These include improvements to the Bayes linear emulator construction process in terms of more advanced active variable selection, selection of polynomial forms specifically appropriate for the history matching requirements, choice of emulator correlation function and appropriate robust assessment of emulator correlation parameters, nugget estimation, Bayes linear emulator and implausibility diagnostics appropriate for history matching and design in multilevel contexts **[R2-R3],** further advances in Bayes linear model discrepancy assessment and representation, and the generalisation of Bayes linear history matching to stochastic models **[R5].** All these advances, published in a series of papers **[R1-R5]**, allow significantly more efficient and general history matching algorithms to be built and have been applied successfully in multiple diverse and challenging scientific contexts e.g. cosmology, epidemiology and oil **[R1-R5]**. These advances were subsequently implemented in the Roxar/Emerson Tempest-ENABLE package by Ian Vernon (Durham) and the Roxar/Emerson team, over the period 2012 to date, as part of a long running consultancy contract between Roxar/Emerson and Durham University Statistics group **[E9]**. This resulted in "an order of magnitude improvement in performance" **[E1]** in terms of the speed and accuracy of the ENABLE software, which allowed it to maintain its competitiveness and profitability in a rapidly evolving market, and its reputation as state-of-the-art history matching and uncertainty assessment software. Roxar/Emerson write (see **[E1]**):

"*The runtime performance of Tempest ENABLE is critical to the commercial viability of the product. During the period 2012 – 2016 many improvements were made to the underlying algorithms in Tempest ENABLE which brought an order of magnitude improvement in performance…These improvements were based on Bayes linear emulation and history matching methodologies developed in the following papers by Durham* **[R1-R4]***. These advances greatly improved the quality of fits of the emulator resulting in substantial improvements in history matching."…"Our collaboration with Durham has allowed us to develop superior implementations of Bayes linear emulators when stochastic forward models are in use* ***[R5]****. This feature is currently unique within the industry."*

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

[R1] Vernon, Ian., Goldstein, Michael. & Bower, Richard G. (2010). Galaxy Formation: a Bayesian Uncertainty Analysis. Bayesian Analysis 05(04): 619 - 670 (with discussion). DOI: 10.1214/10-BA524

Comment: This paper extended history matching techniques for general heavy simulators in multiple directions and demonstrated these improvements on a large and complex model of Galaxy formation. **Awarded the major worldwide prize in Bayesian statistics**: the Mitchell Prize jointly awarded by the American Statistical Association and the International Society for Bayesian Analysis. The transferable techniques developed in this work were directly implemented in ENABLE, and several other scientific disciplines.

[R2] Cumming, J. A. & Goldstein, M. (2009). Small Sample Bayesian Designs for Complex High-Dimensional Models Based on Information Gained Using Fast Approximations. Technometrics 51(4): 377-388. DOI: 10.1198/TECH.2009.08015
Comment: Developed and implemented sophisticated design strategies for multilevel emulators, and strategies for efficient output selection, in a history matching context, and applied them to oil reservoirs.

[R3] Cumming, J. A. & Goldstein, M. (2010). Bayes linear Uncertainty Analysis for Oil Reservoirs Based on Multiscale Computer Experiments. In The Oxford Handbook of Applied Bayesian Analysis. O'Hagan, A. & West, M. Oxford: Oxford University Press. 241-270.
Comment: Developed further and implemented sophisticated design strategies for multilevel emulators, and strategies for efficient output selection, in a history matching context, and applied them to oil reservoirs. Uploaded into Underpinning Research folder.

[R4] Vernon, I., Goldstein, M., Bower, R.G. (2014). Galaxy formation: Bayesian history matching for the observable universe. Statistical Science 29(1), 81–90. DOI: 10.1214/12-STS412
Comment: Invited paper for statistics journal on "**Bayesian Success Stories**", summarising recent advances to history matching for general simulators of complex physical systems.

[R5] Andrianakis, Ioannis, Vernon, Ian, McCreesh, N., McKinley, T.J., Oakley, J.E., Nsubuga, R., Goldstein, M. & White, R.G. (2015). Bayesian history matching of complex infectious disease models using emulation: A tutorial and a case study on HIV in Uganda. PLoS Comput Biol 11(1): e1003968. DOI: 10.1371/journal.pcbi.1003968
Comment: The extension of Bayes linear history matching methodology to stochastic models, and an example of the transferability of the techniques. Applied to analyse a complex stochastic model of epidemiology (HIV in Uganda). Techniques implemented in Enable **[E1]**.

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

Roxar/Emerson and ENABLE

Roxar AS, which owns ENABLE, is an international provider of products and associated services for reservoir management and production optimisation in the upstream oil and gas industry. Working with the Durham Statistics Group has helped Roxar to develop a more successful product, leading to substantial commercial success (see table below). It has also helped Roxar secure long-term technical jobs in its development team and delivered significant impact for its customers. The company is committed to both its support for ENABLE as its flagship product and its continuing work with Durham Statistics Group.

This is how Roxar currently describe the role of ENABLE **[E4, E5]**:

"ENABLE provides mathematical support to reservoir engineers in their use of reservoir simulation software. This support allows engineers to complete tasks like history matching much more quickly than using the simulator on its own and also provides a more rigorous approach to predicting future reservoir performance or optimising field development."

Roxar is headquartered in Stavanger, Norway and operates in 19 countries with around 900 employees. Roxar offers software for reservoir interpretation, modelling and simulation, as well as instrumentation for well planning, monitoring and metering. Roxar was acquired by Emerson Electric Company in April 2009 and is now part of the Emerson Process Management Group.

Financial Impact

The ENABLE product has been very successful. The current list of ENABLE clients includes **[E1]:** [redacted]

[redacted]

This has led to substantial and sustained financial impact. Roxar/Emerson report **[E1]** the following total Tempest ENABLE annual sales figures in USD for 2014 to 2019. Results are reported to Emerson's financial year which runs from 1st October to 30th September.

	[redacted]
2014	
2015	
2016	
2017	
2018	
2019	

Job retention - Research and Development

The ENABLE product has also maintained several long term Roxar employment positions **[E1]:** *"During the period 2014 to date the core Tempest ENABLE development team in the UK is **6 highly technical people (5 PhDs)**. Additional sales, services and support jobs are supported by ENABLE's success."*

Increased Market Competitiveness

Roxar remains committed to the continuation of their support for ENABLE, as evidenced by them integrating it within their flagship TEMPEST simulator package now called TEMPEST-ENABLE, the development of which was part funded by STATOIL **[E3, E6, E8]**.

The implementation within ENABLE of more advanced algorithms resulting from recent research work, by the Durham statistics group, from 2012 onward has led to substantial improvements in the code performance, and kept the ENABLE software highly efficient and competitive in an aggressive market since Oct 2014. The Roxar team have written that **[E1]:**

"*The runtime performance of Tempest ENABLE is critical to the commercial viability of the product. During the period 2012 – 2016 many improvements were made to the underlying algorithms in Tempest ENABLE which brought an order of magnitude improvement in performance. These improvements included more advanced Bayes linear emulator construction strategies, improved experimental and sequential designs, robust correlation length estimation and robust active inputs selection. New Bayes linear emulator diagnostics were introduced which demonstrated, in a visual manner, the improvements in the algorithms. These improvements were based on Bayes linear emulation and history matching methodologies developed in the following papers by Durham* **[R1-R4]**. *These advances greatly improved the quality of fits of the emulator resulting in substantial improvements in history matching."*

Continued Commitment to R&D

Roxar are committed to continuing their relationship with Durham University Statistics Group, funding three consecutive consultancy contracts **[E9]**: June 2012 – May 2015 (GBP135,000), June 2015 – May 2018 (GBP150,000), June 2018 – May 2021 (GBP157,200), to fund Dr Vernon to help implement improvements to ENABLE. They have also funded an iCase studentship (Oct 2018 – Sept 2022, GBP55,000 in addition to full EPSRC contribution) to develop further impact related statistical methodology **[E1].**

Substantial impact in the oil and gas industry

ENABLE facilitates a detailed analysis of oil reservoirs including the quantification of uncertainties vital for forecasting, decision making and hence managing oil assets [**E4-E8**], and therefore has substantial impact on the oil companies who use it. Examples are **[E1]**:

*"Tempest ENABLE is also a key piece of Big Loop and was **instrumental in avoiding a potential loss of $5M** in renewal fees at a large international oil company. Big Loop is gaining traction in the market and is being successfully adopted at major national and international oil companies."* (Big Loop combines geological and reservoir models in the inferential framework, but again uses Tempest-Enable at its core).

Another example is given in **[E2]**, a 2017 press release of a successful long-term joint project by Statoil and Emerson, again using Tempest-Enable at its core. ''The program focused on how E&P companies can improve history matching, uncertainty management and quantification across the entire reservoir characterization workflow through Roxar Tempest ENABLE, Emerson's industry-leading history matching and uncertainty estimation software solution.''

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

[E1] Letter from Robert Frost at Roxar/Emerson detailing, a) description of Enable's place in market, b) list of press releases/brochures, c) evidence of use of Enable by many clients, d) link between DU research and product improvement, e) sales figures for Tempest-Enable 2012-2019.

[E2] 2017 press release re joint Statoil/Emerson project using Tempest-Enable as core: https://www.worldoil.com/news/2017/5/25/in-cooperation-with-statoil-emerson-announces-completion-of-total-uncertainty-management-program. (Site copy taken 14/9/20)

[E3] Emerson main page on the Tempest ENABLE software. Links at bottom of page to several data sheets and articles that describe ENABLE as a core part of the software. Link: https://www.emerson.com/en-us/catalog/roxar-tempest-enable. (Site copy taken 28/2/20)

[E4] Specific data sheet on Tempest ENABLE obtained from link in **[E3]** (on 5/04/19) that describes its strengths, and which specifically mentions Dr Ian Vernon, Durham University.

[E5] Folder containing several data sheets (taken on 5/04/19 from **[E3]**) detailing Tempest ENABLE (to evidence core part ENABLE plays in the software).

[E6] Emerson webpage detailing latest release of Tempest 8.2 (on 8/5/18) that contains ENABLE at its core (see the 2nd paragraph: "…Enhancements to the Big Loop workflow within Tempest ENABLE, Emerson's uncertainty management and history matching module, center on…" Link: https://www.emerson.com/en-us/news/automation/1805-roxar-tempest-8-2. (Site copy taken 28/2/20)

[E7] Emerson Webpage detailing "Reservoir Engineering and Simulation" containing list of products including Tempest ENABLE. Link: https://www.emerson.com/en-us/automation/operations-business-management/reservoir-management-software/reservoir-engineering-and-simulation. (Site copy taken 28/2/20)

[E8] Press release regarding Tempest ENABLE and a case study article. "Press release re Tempest Enable and case study article" (taken on 5/04/19 from **[E3]**).

[E9] Consultancy contracts between Durham University and Roxar/Emerson from 2012-2021.