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| **Institution:** | UDur: University of Durham |

**Unit of Assessment:** Unit 10: Mathematical Sciences

**Title of case study:** History matching and uncertainty assessment in the oil and gas industry

*** Redacted version with confidential information removed ***

## 1. Summary of the impact

ENABLE is a history matching and uncertainty assessment software system for the oil industry, whose inference engine was produced by the Durham Statistics group, based on their research on uncertainty quantification for complex physical systems modelled by computer simulators. The system optimizes asset management plans by careful uncertainty quantification and reduces development costs by accelerating the history matching process for oil reservoirs, resulting in more informed technical and economic decision-making. ENABLE was acquired by Roxar ASA in 2006 and current users include the multinational oil company Statoil. From January 2008 to September 2012 (the most recent set of figures) the turnover attributed to ENABLE was **[text removed for publication]**.

## 2. Underpinning research

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. Much of this work was developed in the context of history matching for oil reservoirs. 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 space is high dimensional and the evaluation of the simulator, for a single choice of inputs, takes many hours.

The Durham group devised a detailed Bayesian solution [1] 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. In order to construct the emulator, the group solved novel problems in prior elicitation, joint Bayesian modelling for multi-level versions of the simulator, experimental design for multi-level computer experiments, and diagnostic evaluation for the resulting construction. This emulator, in combination with an uncertainty representation for the difference between the simulator and the reservoir, formed 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 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 history.

This work was developed under EPSRC funding, from 1993 to 1995, and was published in 1997 [1]. The key researchers for the work were Michael Goldstein, Peter Craig and Allan Seheult, all permanent members of the Durham Statistics group at that time, and James Smith, PDRA on the grant from 1993 to 1995.

## 3. References to the research

The underpinning work for this research was funded by EPSRC, under the Complex Stochastic Systems initiative on the grant `Bayes linear strategies for history matching for hydrocarbon reservoirs' (1993-95, value £105,000).

One of the outcomes of this research was the invitation to present the work at the third Case Studies in Bayesian Statistics meetings at Carnegie Mellon University in October 1995. The Case Study format allowed the Durham group to make a complete presentation of all of the aspects of its research. It appeared subsequently as

**[1]** P.S. Craig, M. Goldstein, A.H. Seheult, J.A. Smith (1997), *Pressure matching for hydrocarbon reservoirs: a case study in the use of Bayes linear strategies for large computer experiments (with discussion)*, in Case Studies in Bayesian Statistics, vol. III, eds. C. Gastonis et al. 37-93. Springer-Verlag.  New York, ISBN 0-387-94990-9. doi:10.1007/978-1-4612-2290-3_2.

Only a few invitations to present a case study at this meeting are made, with the intention of producing very careful and detailed case studies for a small number of substantial applications. The printed version contains a discussion by Galway and Lucas, from the RAND Corporation, who refer to this paper as "superb" and "outstanding". As of 25/10/2013, the paper had 73 citations on google scholar.

Grant applications following from **[1]** have been very successful, resulting in support for postdocs on grants from NERC (under the RAPID programme and the PURE programme), Leverhulme (the Durham Tipping Points project), EPSRC (The Managing Uncertainty for Complex Models consortium, funded by the Basic technology initiative) and industry (for example the Joint Inversion using Bayesian Analysis project, funded by an oil consortium). (Total value of these grants to the Department: £903,000.)

## 4. Details of the impact

As a result of **[1]**, the Durham Statistics group was contracted by Energy SciTech Ltd (a consultancy firm to the oil industry with which we have a long research and consultancy connection, and who provided the reservoir information from which we developed the case study) to write the inference engine for the system ENABLE which optimizes asset management planning and reduces costs by accelerating the history matching process and improving reservoir understanding. Operators now use ENABLE worldwide for a better understanding and measurement of uncertainty in reservoir production performance estimates. Using a Bayesian statistical framework and emulator for the model, based on conventional reservoir simulations, ENABLE provides companies with a rapid understanding of production behaviour and the creation of robust uncertainty forecasts.

The contract[1] for the software was very precise, in specifying that we would implement all of the procedures described in the research case study paper described in section **3**.  For example, under Testing and Acceptance of the Software, it was stated that

"The performance of each Module of the Prototype will be deemed acceptable to both parties if it can be shown that a level of functionality similar to that demonstrated in *Pressure matching for hydrocarbon reservoirs: a case study in the use of Bayes linear strategies for large computer experiments* (case Studies in Bayesian Statistics, III, New York:  Springer) where consistent with Schedule A, has been achieved."

Energy Scitech, and thus ENABLE, was acquired by Roxar in 2006. Energy Scitech existed on sales of ENABLE and services related to ENABLE. When acquired by Roxar it had revenues of **[text removed for publication]** (1 Nov 2004 - 31 Oct 2005) and **[text removed for publication]** (1 Nov 2005 - 31 Dec 2006)[2]. Since then, and throughout the impact period 2008 – 2013, the reach and significance of ENABLE has continued to grow: in the period 2008 – 2013 active users

included **[text removed for publication]**[3], and the total turnover attributed to ENABLE sales by Roxar from 1 Jan 2008 to 30 Sept 2012 was **[text removed for publication]**[4]. In the UK there are currently **[text removed for publication]** staff working full-time on ENABLE, and an estimated **[text removed for publication]** who spend a proportion of their time on the project[3].

Roxar AS is an international provider of products and associated services for reservoir management and production optimisation in the upstream oil and gas industry. It 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.

This is how Roxar currently describe the role of ENABLE[5]:

"History Matching and Uncertainty Quantification. The Roxar ENABLE solution history matches numerous geological scenarios to create simulation models that are fully consistent with their underlying geological interpretation (unlike many current 3D modelling workflows). RMS, Tempest and ENABLE provide E&P companies with a statistical framework for a rapid understanding of production behaviour and the creation of robust estimates from a shared earth model. The result is more informed technical and economic decision-making and a better quantification of uncertainty."

This product has been very successful and as specified in the contract[1] the University has received a royalty each year to date, based on the sales of the commercial product. In particular, in the period Jan 2008 – Sept 2012, **[text removed for publication]** has been received in royalties[6]. Roxar have continued to develop the product, and to pay royalties to the University, and are committed to ensuring that it remains current: from June 2011 – May 2012 Roxar had a consultancy contract for **[text removed for publication]** with the University to consider ways to improve the application of ENABLE for complex oil reservoirs. This was deemed successful and led to a further consultancy contract being agreed, for **[text removed for publication]** from June 2012 to May 2015[6].

As attested by Roxar[7], the software developed in 1998 on the basis of **[1]** remains a key feature of the Tempest ENABLE product. The project to integrate ENABLE into Roxar's Tempest suite was completed in 2012[8]; it brings the Durham developed emulator and subsequent enhancements to a wider global community.

In 2012, Tempest ENABLE was chosen as the uncertainty platform for the multinational oil company Statoil[9]. This has secured funding for the next three years for **[text removed for publication]** software developers in Roxar. The methodology developed in **[1]**, together with the quality of the associated work delivered by Durham, was pivotal to the awarding of this contract[7].

The Tempest ENABLE product has over **[text removed for publication]** active users as of November 2012[7], and can be regarded as one of the most successful uncertainty platforms in the oilfield marketplace, to the point that it has created a new business activity. Roxar states:[7]

"The fast Durham developed emulator enables a rigorous statistical approach to uncertainty quantification. ENABLE was the first commercial product to allow this in the oil and gas industry. Since ENABLE's release several competitors have emerged taking advantage of the approach ENABLE has validated."

The success of ENABLE is confirmed by user feedback. To give one example from the Tempest ENABLE product website[10], Dr Curt-Albert Schwietzer of GSC Reservoir Simulation & Reserves states:

"After using ENABLE for over one year I can say that reservoir simulation without ENABLE is unimaginable."

### 5. Sources to corroborate the impact

1.  Initial contract between Energy SciTech Ltd and Durham University, 1999.

2.  Audited financial statements for Energy SciTech for the period 2004—2006, immediately prior to its acquisition by Roxar AS.

3.  Supporting document from Roxar sent to Durham 27/09/2013.

4.  Audited financial statements for Energy Scitech Ltd covering the period 2008 – 2012.

5.  The Roxar Software brochure, accessible from http://www2.emersonprocess.com/en-US/brands/roxar/reservoirmanagement/ Pages/ReservoirManagementSoftware.aspx

6.  Royalty invoices and consultancy contracts between Roxar and Durham University.

7.  Supporting document from Roxar sent to Durham 27/11/2012.

8.  The press release for the project to integrate ENABLE into Roxar's Tempest suite: http://www2.emersonprocess.com/en-US/news/pr/Pages/1210-Tempest.aspx

9.  The press release describing the contract with Statoil to develop Tempest ENABLE: http://www2.emersonprocess.com/en-US/news/pr/Pages/1210-Statoil-Enable.aspx

10. Customer quote listed under 'Proven results' on the Tempest ENABLE product website http://www2.emersonprocess.com/en-us/brands/roxar/reservoirmanagement/reservoirsimulation/pages/tempestenable.aspx