Institution: Edinburgh Research Partnership in Engineering - ERPE (Heriot-Watt/Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Increasing Oil Recovery by Advanced Reservoir Management

1. Summary of the impact

ERPE research into uncertainty quantification for oil reservoir modelling, described in this case study, has led to 3 impacts in the REF2014 period:

- An additional 3 million barrels of oil (corresponding to $330M of additional income at an oil price of $110/barrel) obtained by a single application of ERPE algorithms to optimising oil recovery from one of BP's North Sea assets;
- Incorporation of ERPE developed code in BP's internal code base;
- Formation of a spin-out company (Epistemy) providing 3 full-time and 3 part-time jobs, with £267k of software sales since 2012.

2. Underpinning research:

The uncertainty quantification (UQ) group in ERPE has carried out a programme of EPSRC, TSB and industry funded research into uncertainty quantification for oil reservoir modelling since 2000. The key researchers involved were: Prof Christie (ERPE, director of the UQ group), Prof Corne (Computer Science (CS)), A Abdollahzadeh (ERPE postdoc), A Reynolds (CS, postdoc), A Gripton (CS, postdoc), Dr Vasily Demyanov (ERPE, lecturer), Dr D Arnold (ERPE, postdoc and Royal Society of Edinburgh Enterprise Fellow).

The aims of this research programme have been (i) to develop and demonstrate algorithms that offer a significant performance gain over the algorithms routinely deployed in the oil industry, (ii) to develop techniques to ensure that forecast uncertainty ranges are robust and not significantly affected by sampling algorithm or model resolution, and (iii) demonstrate the value of geological realism in constraining model predictions.

The impacts claimed here have largely been underpinned by research into the use of stochastic optimisation algorithms for history matching (model calibration), uncertainty quantification and optimisation. References [1 – 5] give examples of this research. The research has been driven by a combination of simplified test problems, used for developing ideas and algorithms, and real examples usually donated by oil companies. The purpose here is to develop algorithms that are capable of deployment on real-world problems (with all the problems of large models, extensive run times etc, that real-world problems bring).

The research underpinned these impacts in the following ways:

- the codes implemented by BP (BOA, MOBOA, [4]) in their internal code base were developed in ERPE in a joint activity with Computer Science at Heriot-Watt, including novel extensions (GuPSO, [2]) to already published algorithms.
- for the spin-out company, the algorithms (single and multi-objective versions of Particle Swarm Optimisation (PSO), Differential Evolution (DE), Bayesian Optimisation Algorithm (BOA) [4]) coded up in the commercial code were those that had been extended and exhaustively evaluated for effectiveness in the UQ group in ERPE. These tests included demonstration that the codes show a 2 – 5 fold speed up over existing, highly-tuned implementations.

3. References to the research

The references identified with * are the ones which best indicate the quality of the underpinning research.

[1] * L Mohamed, M Christie, V Demyanov "Comparison of Stochastic Sampling Algorithms for Uncertainty Quantification", (2010) SPE-119139-PA, SPE Journal, 15(1), 31-38. DOI:10.2118/119139-PA. 41 Google Scholar (GS) citations

This research showed that use of an evolutionary algorithm (such as PSO) combined with a post-processing step based on a Gibbs Sampler yields an equivalent assessment of uncertainty as applying the 'gold standard' Markov Chain Monte Carlo. This paper underpins

the decision to implement evolutionary algorithms with an appropriate Gibbs sampler based post-processor in the commercial software Raven developed by Epistemy (www.useraven.com).

[2] * A Abdollahzadeh, A Reynolds, M A Christie, D Corne, G William & B Davies, "Estimation of distribution algorithms applied to history matching" Jun 2013 SPE Journal. 18, 3, p. 508-517 DOI:10.2118/141161-PA 13 GS citations

[3] M Christie, D Eydinov, V Demyanov, J Talbot, D Arnold, V Shelkov, "Use of Multi-Objective Algorithms in History Matching of a Real Field" (2013), Society of Petroleum Engineers Reservoir Simulation Symposium, 2013, The Woodlands, Texas SPE 163580, DOI:10.2118/163580-MS

Papers [2], [3] also arise from the TSB funded project [G1] aimed at developing significant improvements in history matching capability. [2] describes the use of the BOA, and shows that it performs better than highly developed internal BP code. [3] demonstrates that multi-objective algorithms can offer speed advantages over the equivalent single objective algorithms. As a result of the research described in these papers (and other unpublished TSB work), BP has taken the developed code and coupled it with their TDRM proprietary code, and used the algorithms for optimising well placements.

[4] * Y Hajizadeh, V Demyanov, L Mohamed, M Christie, "Comparison of Evolutionary and Swarm Intelligence Methods for History Matching and Uncertainty Quantification in Petroleum Reservoir Models", in Intelligent Computational Optimization in Engineering: Techniques & Applications, 2010 DOI: 10.1007/978-3-642-21705-0_8 This (refereed) book chapter demonstrates that (applied effectively), modern swarm intelligence algorithms can provide reliable and robust history matching and estimates of future uncertainty. The study showed that both DE and PSO can converge faster than other algorithms tested, and this led to their selection for implementation in Epistemy's commercial code Raven.

[5] A P Reynolds, A Abdollahzadeh, D W Corne, M Christie, B Davies, G Williams "Guide Objective Assisted Particle Swarm Optimization and its Application to History Matching". In Parallel Problem Solving from Nature-PPSN XII (pp. 195-204), 2012. DOI:10.1007/978-3-642-32964-7. This paper shows a novel way to improve the formulation of PSO for large-scale problems where prior knowledge of parameter influence can be exploited. The algorithm has been coded up for the next release of Raven.

Research Grants

[G1] TSB, #100729, BP, ERPE, £808k, "A Novel Approach to Uncertainty Quantification and Risk Assessment in Petroleum Reservoir Developments", 2009–2013.

[G2] Joint Industry Project, £2.8M funding from industry partners, Uncertainty Project Phases I, II, III, IV. ERPE, Anadarko, BP, BG, Conoco, DTI, Eni, JNOC/JOGMEC, Norsk Hydro, Shell, Statoil.

[G3] AWE, £420k, 3 years postdoc funding & AWE William Penney Fellowship – M Christie.

[G4] EPSRC, GR/R63578/01, £125k, M Christie (PI), "JREI:Use of Massively Parallel Simulation for Uncertainty Quantification in Reservoir Engineering", 2002–2005.

[G5] EPSRC, GR/T24838/01, £237k (pre-FEC), M Christie (PI), "Error Models for Sub-Grid Phenomena in Flow in Porous Media", 2005-2008.

[G6] EPSRC, EP/K034154/1, £2.04M, M Christie (Co-I), "Enabling Quantification of Uncertainty for Large-Scale Inverse Problems (EQUIP)", Programme Grant with Stuart (PI), Roberts and Girolami (University of Warwick), 2013-2018.

4. Details of the impact

The research has led to 3 principal impacts:

- application of the algorithms on a North Sea oil field, leading to an additional 3 million barrel recovery (equivalent to $330M additional income at a current oil price of $110/barrel) over their original development plan [S3];
- implementation of ERPE multi-objective optimisation algorithms by BP in their internal 'TDRM' code base and
- formation of a spin-out company to commercialise application of the algorithms developed in the uncertainty group to the oil industry [S1].

The first impact is an additional 3 million barrels of oil obtained by BP using the ERPE multi-objective algorithms. BP has applied the new code base to the task of optimising locations of additional injection and production wells in one of their North Sea fields. The use of the multi-objective algorithms discovered a new well arrangement yielding an additional 3 million barrels over the optimised development plan produced by their engineer. In this case, multi-objective optimisation was of tremendous value as it allowed them to optimise both short-term oil (to recoup the cost of drilling the new wells), and long-term oil (to maximise the profitability) of the project. BP's comment on the project was "*The collaboration between ERPE and BP has resulted in a step-forward in practical, multi-objective optimisation capability for the industry*" [S3].

The second impact is that BP has taken the ERPE multi-objective algorithms, developed in the TSB project [G1] and incorporated them in their internal history matching and optimisation code during 2012 and 2013. The incorporation of the algorithms was assisted by their recruitment of Asaad Abdollahzadeh, one of the ERPE researchers, into BP from Jan 2013.

The third impact was the formation of spin-out company, Epistemy (SC365481) in September 2009 providing 3 full-time and 3-part time jobs. The company has made £267k in sales of its Raven history matching and optimisation software since 2012. It has recently started attending trade shows and generating significant interest (10 strong leads, with one trial set up and one booked for Oct 2013) [S1]. The stochastic optimisation algorithms in the latest release of Epistemy's Raven code (those developed in [G1]) have already been deployed in history matching of real field data by engineers in Japan Oil, Gas and Metals National Corporation (JOGMEC) (DOI:10.2118/164817-MS). JOGMEC's comment on the software was: "*The software is a practical and simple tool for history matching real field data and optimising field developments; it has given us a significant speed improvement over our previous algorithm, and has made it possible to deploy the advanced techniques in Raven within our team*" [S2].

The beneficiaries of all 3 impacts are: practicing reservoir engineers who use the techniques in history matching reservoir models to data (see for example [4] for application to a Russian oil field, and [3] for application of BOA to history matching a BP oilfield, demonstrating a significant performance improvement), and the impact on the UK economy of 3 new full-time and 3 part-time jobs created since 2009 [S1].

Additionally, industry support of £2.8M has been received from 10 international oil companies over 4 three-year phases of a Joint Industry Project [G2]. As a result of the research published, we have also received £420k funding from AWE [G3] to transfer ideas from the oil industry to AWE. The interaction with AWE has led to improvements in their capability [see example in S4], and has underpinned their decision to support EPSRC Programme Grant [G6] by continuing Christie's William Penney Fellowship [G3].

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

[S1] Founder/Senior Executive, Epistemy. To confirm the establishment of Epistemy (SC365481) was in September 2009 and that it provides 3 full time and 3 part time jobs. The company has made £267k in sales of Raven history matching and optimisation software since 2012. www.epistemy.com, software sold through www.useraven.com.

[S2] EOR Division Director, Technical Department Oil & Gas Upstream Technology Unit Japan Oil, Gas and Metals National Corporation will describe how JOGMEC use the software, and

what advantage it gives them over previous tools.

[S3] Manager, Advanced Reservoir Performance Prediction, BP will confirm that BP has applied the new code base to the task of optimising locations of additional injection and production wells in one of their North Sea fields, producing and additional 3million barrels of oil over the optimised development plan.

[S4] An example of improvements in AWE's capability through the ERPE research described above can be found in the document at this link. http://www.awe.co.uk/Contents/Publication/68e180bAWE_Discovery_22.pdf, p. 2-9.