Institution: Heriot Watt University

Unit of Assessment: B11 Computer Science and Informatics

Title of case study: Enhanced reservoir management in the oil/gas sector via new algorithms for large-scale optimization

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

Research in the HWCS Intelligent Systems Lab since 2006 has developed approaches to accelerate and improve large-scale optimization. This has led to new algorithms that enable multiple high-quality solutions for complex problems, either more quickly, with better solution quality than previously obtainable, or both. These algorithms, combined with uncertainty quantification techniques from related research, have been adopted by both British Petroleum Plc (BP) and Epistemy Ltd (an SME serving the oil/gas sector). Impact for BP includes improved business decision-making (relating to ~$330M in turnover),and impact for Epistemy includes sales of £230k.

2. Underpinning research (indicative maximum 500 words)

Large-scale optimization has been a thread of HWCS research since 2006. A 'large-scale' problem either involves many parameters, a time-intensive cost function, or both, and the challenge is to provide good results quickly. Even more significant in many applications is the need to generate a diverse collection of good alternative solutions (again, quickly). This requires novel ways to accelerate 'diversity-enhanced' and exploratory optimisation techniques, which is particularly challenging since such techniques are time-hungry.

The oil/gas sector provides pertinent examples. One is 'history matching', where we identify the oil/gas reservoir parameters that, when simulated, lead to production figures that match historical production. Another is reservoir development planning, where we aim to find the most economically effective schedule for development of a reservoir, in terms of the location and timing of future production processes. In both cases, future, typically billion-dollar decisions need to be based on a representative set of diverse plausible solutions.

Corne has addressed the underpinning challenges by exploring novel ways to use machine learning within optimization. One thread of this research explores how learning methods, such as decision trees or Bayesian networks, can be used during optimization to derive, adaptively and dynamically, models of good solutions, and these models can then be used to bias progress towards better solutions. For example, in [1] we presented a hybrid of evolutionary search and decision tree learning that outperforms state of the art algorithms, increasingly so for larger scale problems. A KTP project (06/11--08/12, £86k) developed further variants of this approach, and supported its deployment in Epistemy Ltd.'s current 'Raven' software product for the oil and gas sector.

In parallel, and supported partly by a BP-led TSB project (11/09--08/13, £698k to HWU, £290k to HWCS) as well as a SEAS DTC award with BAE Systems (07/09--03/10, £26k), we have explored how to accelerate the diversity-enhanced exploration provided by probabliistic and/or multiobjective search. Relevant outcomes include effective approaches for problems with many optimization objectives [5], and approaches to multiobjective optimization when the cost function is particularly costly [6]. The TSB project explored this thread specifically for both the 'history matching' and reservoir development planning tasks; in [2] we showed how Bayesian Optimization could be successfully designed and adapted to outperform previous history-matching techniques. Subsequent work explored further algorithmic developments for these problems, including an entirely novel way to engineer particle swarm optimization for large-scale problems where prior knowledge of parameter-interaction can be exploited [3], and novel ways to hybridize Bayesian and particle-swarm optimization [4], Translation of the underpinning research into impact was enabled by conjunction with uncertainty quantification underpinnings by HWU's Institute of Petroleum Engineering (IPE).

In brief, HWCS research provided methods to obtain multiple high-quality distinct solutions quickly, while IPE research provided techniques to reason about and visualize those solutions to support decision-making. Key researchers involved (excluding those focussed entirely on uncertainty quantification) were Prof Christie (IPE), Prof Corne (HWUCS), A Abdollahzadeh, A. Reynolds, and M. Tapley (RAs, joint IPE and HWCS).

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

1.Sheri, G., & Corne, D. (2010, July). Learning-assisted evolutionary search for scalable function optimization: LEM (ID3). In Evolutionary Computation (CEC), 2010 IEEE Congress on (pp. 1-8). IEEE. (The IEEE Congress on Evolutionary Computation is one of the three major international, archival events in this field, and the most prestigious IEEE one. It was rated 'A' in the commonly used Australian Research Council ERA exercise.)

2. Abdollahzadeh, A., Reynolds, A., Christie, M. A., Corne, D., Davies, B. & Williams, G. "Bayesian Optimization Algorithm Applied To Uncertainty Quantification" Sep-2012 SPE Journal. 17, 3, p. 865-873 http://dx/doi.org/10.2118/143290-MS (the SPE (Society of Petroleum Engineers) Journal is one of the few primary media for scientific publications relevant to the oil/gas engineering sector)

3. Reynolds, A. P., Abdollahzadeh, A., Corne, D. W., Christie, M., Davies, B., & Williams, G. (2012). Guide Objective Assisted Particle Swarm Optimization And Its Application To History Matching. In Parallel Problem Solving from Nature-PPSN XII (pp. 195-204). Springer Berlin Heidelberg. http://dx.doi.org/10.1007/978-3-642-32964-7 (PPSN is one of the three major international, archival events in this field, and the major European-centred one. It was rated 'A' in the commonly used Australian Research Council ERA exercise.)

4. Reynolds, A. P., Abdollahzadeh, A., Corne, D. W., Christie, M., Davies, B., & Williams, G. (2011, June). A Parallel BOA-PSO Hybrid Algorithm For History Matching. In Evolutionary Computation (CEC), 2011 IEEE Congress on (pp. 894-901). IEEE. (see notes for ref 1).

5. Corne, D. W., & Knowles, J. D. (2007, July). Techniques For Highly Multiobjective Optimisation: Some Nondominated Points Are Better Than Others. In Proceedings of the 9th annual conf. on Genetic and evolutionary computation (GECCO) (pp. 773-780). ACM. (GECCO is one of the three major international, archival events in this field. It was rated 'A' in the commonly used Australian Research Council ERA exercise. 122 citations to date)

6. Knowles, J., Corne, D., & Reynolds, A. (2009, January). Noisy Multiobjective Optimization On A Budget Of 250 Evaluations. In Evolutionary Multi-Criterion Optimization (EMO) (pp. 36-50). Springer Berlin Heidelberg. (EMO is the primary international publication focussed on evolutionary multiobjective optimization.)

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

The underpinning research has led to impact primarily because (when used in synergy with the uncertainty quantification underpinnings via IPE) it has led to significantly improved capability in dealing with optimization problems in the oil/gas sector, validated by many tests involving data from real oil/gas fields. For example, both single and multi-objective versions of the underpinning algorithms have been tested on real field examples, including a Russian field with 15 years of history and 95 wells (http://dx.doi.org/10.2118/163580-MS). These tests showed minimal 2 to 5-fold speedup in efficiency over competing algorithms including BP's internal highly efficient code. Meanwhile refs [2,3,4] and others all show a combination of 2fold--5fold speedup over previous methods, usually in conjunction with obtaining both more and better-quality solutions than previous methods. In addition, the use of multiobjective approaches is new in the oil industry (with benefits in enabling users to visualise a range of salient trade-offs in potential solutions, as well as

supporting efficient diverse search) and the underpinning work has led to considerable internal interest within BP, as well as helped Epistemy become the first to market software to the oil/gas sector that includes multiobjective approaches.

In detail, the research has led to two principal impacts in the assessment period:

Impact: BP Plc.

BP implemented algorithms generated from this research in their internal 'TDRM' code base, and some of their asset teams have applied the algorithms, leading to reservoir management planning decisions during 2013. In detail, the software implemented by BP (BOA, MOBOA, see [2,3,4]) in their internal TDRM code base were developed as part of the BP-led TSB project at Heriot-Watt in a joint activity between the IPE and HWCS. During 2013, BP has applied this 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 yielded an additional three million barrels over the optimised development plan produced by their engineer. This has translated into a business decision that has a positive $330M impact on BP's turnover. In this case, our multi-objective optimisation approach 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 Heriot-Watt and BP has resulted in a step-forward in practical, multi-objective optimisation capability for the industry".

Impact: Epistemy Ltd

Epistemy Ltd is an SME serving the oil/gas sector. Key algorithms from the research described are deployed in Epistemy Ltd.'s main software product, called 'Raven', which supports reservoir engineers in history matching and reservoir development planning. Specifically, Raven currently includes versions of the Bayesian Optimization algorithm and its hybrids with particle swarm optimization (PSO), as well as multiobjective versions of each of these, which were developed in the BP-led TSB project (Epistemy were subcontracted to commercialise the research). Relevant sales in the period have been £230k, of which £107,000 is directly attributable to the underpinning research described above, and we know of at least one case where the software has already been deployed in history matching of real field data by engineers in one company (http://dx.doi.org/10.2118/164817-MS). In addition, the underpinning research- via funding procured on the basis of it, as well as its results, has been central to Epistemy's maintenance of a team of 3 software engineers, as well as a 6-month consultancy post and four HWCS student placements during the period.

5. Sources to corroborate the impact (indicative maximum of 10 references)
Impact (i): Company is Epistemy, www.epistemy.com , and software is sold through www.useraven.com
Founder Director, Epistemy

Impact (i) Chief Technical Officer, London, JOGMEC (Japanese Oil and Gas organization) is a client of Epistemy, and can corroborate accounts of Raven's deployments in Japan.

Impact (ii): BP, Reservoir Engineer