

<b>Institution:</b> University of Strathclyde		
<b>Unit of Assessment:</b> B11 Computer Science and Informatics		
<b>Title of case study:</b> Application of autonomous intelligent (AI) planning in drilling services industry automation		
<b>Period when the underpinning research was undertaken:</b> 2003 – 2011		
<b>Details of staff conducting the underpinning research from the submitting unit:</b>		
<b>Name(s):</b>	<b>Role(s) (e.g. job title):</b>	<b>Period(s) employed by submitting HEI:</b>
Maria Fox	Professor	01/10/2003 – 31/10/2011
Derek Long	Professor	01/10/2003 – 31/10/2011
<b>Period when the claimed impact occurred:</b> 2014 – December 2020		
<b>Is this case study continued from a case study submitted in 2014?</b> No		
<p><b>1. Summary of the impact</b></p> <p>Underpinned by fundamental research in autonomous intelligent (AI) planning at Strathclyde, plan-based control has been deployed by multinational energy industry technology company Schlumberger to support automation of the well construction process. This represents a step-change in the technology applied to automatic drilling operations, with economic, efficiency, safety and environmental benefits, and has supported Schlumberger's strategic objective to move its services up through levels of automation. A range of impacts have been realised including: technology innovation and new product development; improvements in well construction processes including time savings (for example a 20% increase in drilling rate) and cost savings (estimated at USD300,000 per well), improved drilling consistency and reduced environmental footprint; and economic impacts including product sales and industry partnerships (for example with Exxon Mobile and Honghua Electric). Schlumberger is now also applying this automation technology to borehole logging and logistics.</p>		
<p><b>2. Underpinning research</b></p> <p>Fox and Long, together with research staff colleagues Amanda Coles (née Smith) and Andrew Coles, carried out fundamental research in autonomous intelligent (AI) planning at the University of Strathclyde between 2003 and 2011. A key focus of this research was temporal and numeric planning and plan validation.</p> <p><b>Defining modelling language variants</b></p> <p>Fox and Long defined the syntax and semantics of the modelling language variants PDDL2.1 and PDDL+ [R1] in this period, and pioneered work in planning algorithms for management of the expressiveness of these languages. In 2003, PDDL2.1 introduced the durative action model and the continuous effect, and provided a complete formal semantics. It was adopted by the international planning research community as the standard language for generic temporal planning. Almost all temporal planning research published by international researchers since 2003 has been based on PDDL2.1. Fox and Long later extended PDDL2.1 into PDDL+ [R1], providing constructs for modelling continuous processes and external events, and a formal hybrid automaton semantics.</p> <p><b>Creation of a planner and plan validation system</b></p> <p>Fox and Long had jointly chaired the Third International Planning Competition, held in 2002, and the on-going community-wide discussions and challenges, which built on that competition, significantly influenced the research of the international AI planning community in the following years. For Fox and Long, a main theme was the building of the planner, POPF (Partially Ordered Planning Forward) [R2], that is the core technology underpinning the commercial exploitation by Schlumberger. In terms of key research content embodied in this work, POPF was the first temporal planner to properly handle concurrent activities [R3] and to allow continuous change of numeric quantities to occur, and be referenced, during an action [R4].</p>		

A plan validation system, VAL [R5], was designed and built to enable automated plan verification. It was the first automated plan verification system capable of verifying proper management of temporal and numeric constraints in a plan. VAL has been extensively used in the AI planning research community ever since its introduction. Furthermore, VAL is an essential component in the plan-based automation toolkit being used by Schlumberger. VAL is capable of verifying plans built from models using the key features of PDDL2.1 and PDDL+, outlined previously, but there remain very few planners capable of constructing such plans.

Both POPF and VAL have been benchmarking systems in the international planning research community since 2003. POPF has become the canonical temporal planner, used as the baseline for other temporal planners to beat, and appears in empirical comparisons in many research publications. VAL is still the only automated plan validation system that covers the full temporal language of PDDL2.1. It has been used by the international community since 2003, and is maintained as a community resource on GitHub.

### Advances in temporal and numeric planning

Based on the core work established in POPF and VAL, Fox and Long have developed new fundamental methods for generic temporal and numeric planning. For example, the Temporal Relaxed Planning Graph (TRPG) [R6], first developed in POPF, has been adopted by all temporal planners that support concurrently planned actions. The innovation in the TRPG is the definition of a powerful temporal relaxation enabling efficient search.

### 3. References to the research (Strathclyde affiliated authors in **bold**; FWCI at 02/02/2021)

- R1 Fox, M., & Long, D.** (2006). Modelling mixed discrete-continuous domains for planning. *Journal of Artificial Intelligence Research*, 27: 235-297. <https://doi.org/10.1613/jair.2044> [FWCI: 1.02]
- R2 Coles, A., Coles, A., Fox, M., & Long, D.** (2010, April). Forward-chaining partial-order planning. In *Proceedings of the International Conference on Automated Planning and Scheduling*, 20(1). Available from: <https://bit.ly/2Yi3Jxv>
- R3 Coles, A., Fox, M., Halsey, K., Long, D., & Smith, A.** (2009). Managing concurrency in temporal planning using planner-scheduler interaction. *Artificial Intelligence*, 173(1): 1-44. <https://doi.org/10.1016/j.artint.2008.08.003> [FWCI: 3.66]
- R4 Coles, A. J., Coles, A., Fox, M., & Long, D.** (2009, July). Temporal Planning in Domains with Linear Processes. In *Proceedings of the 21st International Joint Conference on Artificial Intelligence*, 1671-1676. <https://www.ijcai.org/Proceedings/09/Papers/279.pdf> [FWCI: 6.54]
- R5 Fox, M., Howey, R., & Long, D.** (2005, July). Validating plans in the context of processes and exogenous events. In *Proceedings of the Twentieth AAAI Conference on Artificial Intelligence*, 1151-1156. Available from: <https://bit.ly/3cdPyBE>
- R6 Coles, A., Fox, M., Long, D., & Smith, A.** (2008, July). Planning with Problems Requiring Temporal Coordination. In *Proceedings of the Twenty-Third AAAI Conference on Artificial Intelligence*, 892-897. <https://bit.ly/2NBI6qV>

**Notes on the quality of research:** The FWCI scores noted demonstrate that these publications have had higher than average influence on the academic field. Since 2003 the research has been supported by some GBP1,900,000 of competitively won research funding, with two key EPSRC awards supporting the development of POPF (Long, Illes, Fox, *Automated Modelling and Reformulation in Planning*, 01/01/2009-30/11/2012, GBP343,967; McArthur, Long, Bell Fox, *Planning in Mixed Discrete-Continuous Domains*, 01/06/2006-31/12/2009, GBP490,025). VAL, initially developed in 2003, was extended and refined under the latter award.

### 4. Details of the impact

#### Context

Impact has been created through the commercial exploitation by energy industry multinational Schlumberger of the AI planning tools developed by Fox and Long. This has resulted in a step

change in the technology applied to automatic drilling operations, with economic, efficiency, safety and environmental benefits.

Schlumberger is the world's leading provider of technology and digital solutions for reservoir characterisation, drilling, production, and processing to the energy industry. The company supplies an extensive range of products and services, from exploration through production, with a major focus on delivering hydrocarbon reservoir performance sustainably. In terms of scale, the company has product sales and services in more than 120 countries, employed approximately 82,000 people (representing over 170 nationalities) as of the end of third quarter of 2020, and reported revenues of USD32,920,000,000 in 2019.

### From research to impact

Schlumberger became aware of Fox and Long's work on planning with continuous processes through the company's participation as an industry partner in the EPSRC Autonomous Intelligent Systems programme in 2011. Their research has subsequently been instrumental to the company's introduction of autonomous directional drilling [S1]. After initial evaluation, the company engaged Fox and Long as consultants from 2013, during which time they assisted with the development of an architecture for the later adoption of their methods in the application of automated drilling [S1]. Both Fox and Long joined Schlumberger as employees in 2016.

The following impacts have been realised during the REF assessment period:

- Technology innovation, new product development, demonstration and validation;
- Improvements in well construction processes including time and cost savings, improved drilling consistency and reduced environmental footprint;
- Economic impacts including product sales and industry partnerships.

The development and implementation of AI planning supported Schlumberger's strategic objective to move its services up through levels of automation, the scale of the reach and significance of the impact realised set out clearly by the company's Vice President for Technology Development, Well Construction Division:

*'The real step change in our approach to automate highly dynamic and uncertain drilling process started when we engaged Derek and Maria first as consultants and eventually as full-time employees. Their work on the AI planner has become the core of our present and future automation products and services. We have established two large engineering centers, one in Houston, Texas and the other one in Beijing to engineer the research prototype that Derek and Maria developed into commercial products' [S2].*

### Impact 1: Technology innovation, new product development and demonstration

In the period 2013-2015, the POPF planner as developed by Fox and Long was trialed by Schlumberger and a demonstration system was built to explore the potential of using POPF to automate drilling in US land operations. In 2016-17, Schlumberger carried out field tests using POPF, with the intention of identifying the commercial potential of the plan-based automation of drilling.

Concurrently, Schlumberger began the construction of a commercial planning system under the direction of Fox and Long. This led to the development of a next generation planner using methods pioneered in POPF. In subsequent deployments, the new planner was used to generate the action sequences, timing, and parameters (collectively known as plans), needed to reach a given depth. The plans generated vary depending on the hole depth, trajectory, formations and other factors. Preliminary results from field deployments confirmed the potential of the plan-based automation method to speed up the drilling process and provide associated costs savings.

The underpinning technologies built on the POPF planning tool and VAL plan validation system are now embodied in the Schlumberger commercial DrillOps on-target well delivery solution [S3] available within Schlumberger's DELFI cognitive exploration and production (E&P) environment [S4].

Also within the DELFI environment, the DrillPlan solution, which supports the initial well construction project planning phase, works in tandem with the subsequent automation of the drilling process via the DrillOps solution. The two solutions operate as a closely coupled pair in delivering increased automation in well construction.

### **Impact 2: Improvements to well construction processes: efficiency, consistency and reduced environmental risks**

The implementation of AI based planning through the DrillOps and DrillPlan solutions represents a step-change in well exploration and construction. Previously, the industry standards were manual planning and a process known as scripting, in which a pre-written set of instructions, a script, inform the drilling process. Both processes come with considerable drawbacks: manual planning is time-consuming and vulnerable to human error, and scripts – although a significant improvement on purely manual planning – are usually written for a specific location, and thus lack the flexibility to be shared between drills at different sites. Both approaches can therefore lead to inconsistent drilling, delays, additional costs and errors, which may be dangerous or environmentally damaging.

Automation provides numerous benefits over both manual and scripting approaches. It results in greater efficiency and improved consistency of drilling operations. In contrast to scripting, which typically produces scripts specific to individual drill sites, automation is also a more flexible approach and thus applicable to a wider range of drill sites. This saves considerable time and allows engineers working in similar geological areas to share solutions to problems, resulting in significant efficiency improvements. In these ways the capability of automating plan generation has advanced the state of the art in automation techniques in well construction.

The transformative nature of the impact realised through the DrillOps solution is summed up by Schlumberger's Research Programme Manager for Automation and Planning at the company's Cambridge Research Centre:

*'The work has provided wide reaching business impact, such as through the DrillOps autonomous drilling solution, which is not incremental but marks a fundamental shift in the way we approach automation both within our own operations and in solutions we are developing with major oil and gas operators...Automation, through temporal planning enabled by the work of Fox and Long, creates consistency of operations, which drives safety, reduces time-to-target, and the minimisation of environmental footprint' [S1].*

Specific operational performance improvements from proof-of-concept deployment in North America, the Middle East and Mexico include [S5]:

- Improved drilling efficiency: a 20% increase in the drilling rate of penetration (ROP - the speed at which the drill bit can break the rock under it and thus deepen the wellbore);
- The ability to apply standardised procedures throughout a fleet of rigs was found to reduce non-productive time; tool failure non-productive time was reduced by 90% after the roll-out of the DrillOps solution;
- Analysis of drilling operations under manual and automatic control demonstrated that automatic control resulted in improved procedural adherence which has associated consistency and safety benefits, as well as reduced environmental footprint and risk.

### **Impact 3: Commercial implementation and associated economic impact**

Since its commercial deployment started in 2019, the current generation of automated drilling products are used on 27 drilling land rigs [S1], with each rig capable of drilling about 15 wells per year. The operational benefits outlined above are estimated to transfer into operating cost savings of around USD300,000 per well or USD4,500,000 per rig per annum [S6].

In operational deployment, the step-change in operational consistency that the technology helps to deliver was reported in the Schlumberger financial results as a technical highlight of quarter 3

2020 [S1]. This included reporting on deployment in Saudi Arabia where over 63,000ft had been drilled using the DrillOps solution, with a 17-30% improvement in rate of penetration [S7].

In 2020, Schlumberger entered into commercial agreements with major global energy industry partners to integrate automation products including the DrillOps solution in Schlumberger systems developed for these partners. These include:

- Schlumberger and ExxonMobil, the world's largest oil company, finalised an agreement allowing ExxonMobil to deploy the DrillOps solution as part of the deployment of digital drilling solutions around planning, execution, and continuous improvement through learning [S8];
- Schlumberger and Chinese-based company Honghua Electric Co Ltd entered into a memorandum of understanding for the integration of the DrillOps solution into all new rigs manufactured by Honghua [S8]. Schlumberger's share value increased following this announcement.

#### **Impact 4: Other applications of the planner within Schlumberger**

The flexibility of the approach to AI planning, based in the Strathclyde underpinning research and embodied in the DrillOps solution, has allowed Schlumberger to implement it in other aspects of its services business [S1].

##### **Wireline operations**

Known as wireline operations, well measurement operations involve the deployment of sensors and associated transceivers via boreholes. These processes are typically operated manually, but this is accompanied by difficulties in controlling the winch, directing the cable and moving it a fixed speed. Schlumberger has successfully automated this process using the planner. As of 2020, Schlumberger's system of automated wireline operations is currently under field test.

##### **Logistics**

The logistics and product delivery requirements for well drilling are very large and complex, requiring a wide range of equipment and experienced staff, from a variety of locations, to all arrive at a drill site on a set day. Schlumberger has used its planner to successfully automate some aspects of this process in specific applications, with full deployment in 2020.

These new applications demonstrate the flexibility and broad applicability of the planner and its continued importance for Schlumberger's operations.

#### **5. Sources to corroborate the impact**

- S1** Corroborating statement from Research Programme Manager, Automation and Planning, Schlumberger Cambridge Research, dated 25 November 2020.
- S2** Corroborating statement from Vice President for Technology Development, Well Construction Division, Schlumberger Cambridge Research, dated 3 December 2020.
- S3** Schlumberger DrillOps on-target well delivery solution information <https://bit.ly/3ts0pxg> [accessed 18 February 2021].
- S4** Schlumberger DELFI Cognitive E&P Environment <https://bit.ly/30RDXI4> [accessed 1 March 2021].
- S5** Schlumberger, 'Digital drilling system aims to close gap between well plan, rig workflow', *Drilling Rigs & Automation*, September/October 2020, pp.27-29. <https://bit.ly/3s3Sbvc> [accessed 25 January 2021].
- S6** Corroborating statement from Research Programme Manager, Automation and Planning, Schlumberger Cambridge Research, dated 16 March 2021.
- S7** Schlumberger Financial Results Quarter 3 2020 <https://bit.ly/3clUGMQ> [accessed 17 March 2021; p.6 of pdf version].
- S8** Schlumberger Financial Results Quarter 2 2020 <https://bit.ly/3ltLVKL> [accessed 15 March 2021; p.6 of pdf version].