Institution: University of Leeds

Unit of Assessment: B10, Mathematical Sciences

Title of case study Case Study 6: Cost-effective simulation and prediction of explosions for military and public safety, and for improved oil extraction

1. Summary of the impact

The Leeds unit's MoD-funded research programme in hypervelocity impact dynamics has: saved the MoD two years in ballistic development and £1.5m–£2m in costs; guaranteed robustness and reliability of MoD computations; enabled the MoD to deliver advanced research output cost-effectively under severe budgetary pressures; continued to underpin a £4m annual income for the MoD's *War Technology* consultants QinetiQ; provided the MoD with a world-leading explosion-simulation capability. MoD codes underpinned by the Leeds research have, during the REF period, led to a reduction in front-line casualties of British Forces in Afghanistan and Iraq, and enabled government agencies to make quantifiable assessments of threats to transport and public-building infrastructure, e.g. in the planning of the 2012 Olympic Games. QinetiQ have used the codes with industry to develop a new explosive perforator for oil extraction that has: "*halved the R&D process, time-to-market and cost of oil-well exploitation*"; improved oil flows by 30-40% in tests undertaken by oil companies, and; yielded substantial (but confidential, see §**4e**) recurrent licensing royalties.

2. Underpinning research

Background

Between the mid-1980s and 2000, MoD Fort Halstead ─ formerly RARDE, DRA and DERA; now QinetiQ ─ funded a research programme [5,6] in Applied Mathematics at Leeds on the simulation of hypervelocity impacts; specifically, the pitting of supersonic-aircraft windscreens by airborne water droplets, and the penetration of vehicular armour by ballistic weapons. The research improved the MoD's existing simulations, which suffered *"significant limitations"* [B], on two fronts: (a) deficient modelling of the underlying physics, and; (b) restricted computational capability due to inefficient algorithms and insufficient memory. While the MoD addressed "(a)" in-house through improved material models, "(b)" was addressed by the Leeds research group through the development of innovative computational strategies that delivered improved ─ that is, more efficient and stable ─ simulation capabilities using reduced computational resources. These strategies were successfully incorporated into the MoD's ballistic-simulation software-development programme, and subsequently used by QinetiQ to generate impact through the diverse applications (presented in §**4**) in military, private and industrial (oil-extraction) sectors.

Personnel (<u>all</u> Leeds-based)

The MoD research group in Leeds' Department of Applied Mathematics comprised (the late) Professor F A Goldsworthy (SRF, 1993-1996), Dr S B Maunder (PDRF, 1993-1998) and Professor M A Kelmanson (permanent staff, 1993-present). From 1995-2000, Kelmanson was Project Manager, the MoD equivalent of P.I., in which role he was sole supervisor of Dr U Mullane (PDRA, 1994-1995) and Dr D Wilson (PDRA, 1996-1999) on MoD grants totalling £160k [5,6].

Publications and Research Outputs

Research outputs from the programme were almost exclusively in the format of regular, contractually required, substantial MoD *Working Papers* which, designated as "*Restricted*", were circulated within only MoD establishments. Kelmanson wrote four such papers (and his PDRAs nine) of which [1] underpins most directly the impact of the research. Submission to peer-reviewed international journals was occasionally possible following extensive MoD internal vetting; in this context, papers [2,3] emanated from two of Kelmanson's *Working Papers*. The *"significant journal paper"* [A] by Kelmanson and Maunder [4] (the primary paper of this case) summarises the main research of the Leeds group between 1993 and 1999.

Optimization of Computational Resources

Needing to undertake *"significantly more complex and larger simulations"* [B], the MoD funded the Leeds group to undertake research into *adaptive techniques*, whose distinctive strength, absent from standard approaches, is their inherent ability to resolve phenomena occurring *contemporaneously* over widely disparate length scales. That is, at a given time, adaptive techniques allow physical activity to be simulated on a hierarchy of co-existing, unstructured, "coarse-to-fine" computational grids. Adaptive techniques therefore automatically

concentrate/divert computational resources into/from regions where there is physical activity/quiescence (or geometrical complexity/simplicity); this optimizes the efficiency of simulations since detailed computations occur only where necessary ─ as defined by pre-specified *adaption criteria*. In addition, adaptive grids admit *automatic* and *dynamic* grid refinement and coarsening in response to the evolving physics, making the techniques versatile, flexible and computationally cost-effective, since computer memory is dynamically released back into the system when and where high resolution is no longer required. The Leeds group's research and development [1,2,3,4] culminated in the implementation and validation of a fully automated dynamically adaptive technique that was embedded into the MoD's simulation capability, known as "GRIM", for subsequent use in military, civilian and industrial applications.

Validation of the Research

The computational efficiency of Leeds' adaptive techniques was quantified in [4] through application to test ballistic-penetration problems, supplied by the MoD, on: (i) the simulated penetration of protective armour by a hypervelocity rod, and; (ii) the simulated implosion of a spherical shell (for which there is an analytical solution). In [4], it is demonstrated that Leeds' methods require respectively only 15% and 25% of the memory and CPU of the equivalently resolved non-adaptive techniques applied to the same computationally intensive test problems. Additionally, in [3], a pioneering error analysis is performed of an adaptive form of the difference equations that approximate the transient equations of motion of solid mechanics. This analysis enables explicit determination of the conditions under which the Leeds group's methods are computationally stable, thereby providing the MoD with *"the confidence in the numerics to be able to develop physically based material constitutive models and equations of state"* [B] that enabled it to continue its research programme. So ahead of its time was the Leeds group's organic approach in [4] that it was not until 2011 that a competitive approach emerged, via an entirely independent (genetic-algorithm) theoretical and computational route (http://dx.doi.org/10.1007/s00500-010-0684-x): contemporaneous alternative approaches required either an *a priori* knowledge of the location of the regions to be resolved, or were applicable only to steady-state problems.

3. References to the research

In the following list, references best indicating the quality of the research are starred, and all Leeds staff appear in bold font. All documents are available on request.

[1] **Kelmanson, M.A.**, Error analysis of a 2-D Eulerian impact code, *Defence Research Agency Working Paper* D/ER1/9/4/2062/142/RARDE/**6**, 65pp., 1993.

[2*****] **Kelmanson, M.A.**, Unstructured rectangular adaptive-mesh generation for 2-D conservative schemes, *Appl. Math. Lett.*, **6(2)**, 17-21, 1993. (http://dx.doi.org/10.1016/0893-9659(93)90005-8)

[3*****] **Kelmanson, M.A.**, Truncation errors in a 2-D hyperbolic PDE integration scheme, *Math. Engng Ind.*, **6(3)**, 171-183, 1997.

[4*****] **Kelmanson, M.A.** and **Maunder, S.B.**, Modelling high-velocity impact phenomena with unstructured dynamically-adaptive Eulerian meshes, *J. Mech. Phys. Solids*, **47(4)**, 731-762, 1999. (http://dx.doi.org/10.1016/S0022-5096(98)00091-X)

[5] MoD grant, "Adaptive Meshing for Impact Dynamics", DRA WSFH/U2122C (grant holder **Goldsworthy, F.A.** & Project Manager **Kelmanson, M.A.**, £74k, 1995-97).

[6] MoD grant, "Adaptive Meshing for Impact Dynamics", DERA WSS/U6884 (grant holder **Goldsworthy, F.A.** & Project Manager **Kelmanson, M.A.**, £43k + £43k, 1998-99 + 1999-2000).

4. Details of the impact

Provenance of corroboration

The Leeds MoD group conducted its research on a commercial-in-confidence basis, funded [5,6] by the MoD (formerly as RARDE, DRA and DERA; now as the private company QinetiQ). The Leeds research underpinned the MoD's ballistic-simulation computational code — known as "GRIM" — that was developed by QinetiQ for its main UK customer, Dstl, both of whom are in the rare position of being able to provide corroborative evidence of impact. QinetiQ's Senior Research Fellow, the current President of the *International Ballistics Society* [E], has accordingly provided two supporting statements, namely: [B] a generic summary of the end-user benefits accrued, and;

[C] a review of specific impacts, in diverse areas, together with dates. Both the content of [B,C] and the claims made in this case are "*fully endorsed*" [D] by the current Programme Weapons Leader at Dstl (the main end-user of the GRIM codes underpinned by the Leeds' research), who states *"I have been so impressed by the capability that it [GRIM] provides to [the] MOD, that I have continued to fund a number of developments … the numerical simulation capability has allowed the MOD to maintain an international credibility in the face of a changing research focus and financial pressures*" [D].

The following list of areas in which GRIM has been applied at both national and international levels bears testimony to both the reach and significance of the impact generated by the underpinning Leeds research. Unless otherwise stated, all claims and quotes in **(a)–(b)** and **(c)–(f)** refer to [B] and [C] respectively.

(a) R & D cost benefits for the MoD

QinetiQ states that the Leeds research was *"seminal to the development of [its] current capability"* for several reasons, including enabling the MoD to focus on a development path that saved the company *"2 years in development work and £1.5m–£2m in costs and guaranteed a method that was robust and worked."* QinetiQ add that "*Leeds research has continued, up to the present day, to underpin the annual income (£4m) of the Warheads Technology Group at Fort Halstead*".

The Leeds research underpinned the validity of QinetiQ's numerics and demonstrated the benefits of adaption as an effective approach towards predictive numerical simulation, as a result of which it enabled QinetiQ to develop what it describes as an *"integrated numerical simulation-experiment methodology"* that it is now deploying *"over a widening number of areas with significant cost savings."*

QinetiQ uses the adaptive numerical simulations to *"routinely develop concepts without having to resort to large numbers of experimental trials with significant cost savings".* As an example, the company has described how it recently used simulations to develop an explosively formed projectile verified at one-third-scale using three experiments, so that only one experiment was needed to validate the full-scale prediction. QinetiQ asserts: "*Previously this would have required up to 10–20 experiments",* and; *"This has enabled the MoD research programme, under severe budgetary pressures, to continue to deliver advanced research output cost effectively."*

(b) International recognition for the UK

The Leeds research underpinning QinetiQ's numerical simulations has given the company a position of international expertise in the field: *"In this regard we now have a world leading capability in our approach, which is unique to the UK and Europe and generally in the USA,"* the company states. The ability to advise others and share the research has also given QinetiQ credibility and enabled collaboration on cutting-edge research with international allies: *"By being able to share this research with our collaborators in the US National Laboratories we were able to establish the UK as being credible, providing us access to related US research with significant benefits to the UK."*

In more general terms, QinetiQ states: *"The Leeds research helped the UK maintain a leading internationally recognised capability in numerical research, its ability to write 3rd generation software and its application in advanced and complex problems of interest to the defence and security industries."*

QinetiQ continues to benefit from the Leeds research as it builds on its expertise in the area of numerical simulation. The company states: *"We are currently [2011] developing a new code with a completely different strength treatment, which would not have been possible without the underpinning provided by the Leeds research."* [A]

(c) Protecting the lives of the armed forces

The advanced numerics of GRIM, developed with support of the Leeds research, have been used by QinetiQ to rapidly assess new threats to the British Armed Forces in Afghanistan and, latterly, Iraq. Between 2003 and the present day, GRIM has been used extensively in the battle against improvised explosive devices by allowing Dstl to develop new countermeasures for deployment on vehicles and body armour, and in the protection of military bases, all of which has led to a *"resultant reduction in front-line casualties".* QinetiQ further state that *"Without the Leeds work we*

*would not have been able to develop our physically based material algorithms in a **predictive** capability to be able to respond to these urgent operational requirements."*

(d) Protecting the public

The simulation system has also found civilian applications. Between 1995 and the present day, QinetiQ has supported other government agencies to assess the effects of different threats to transport and public-building infrastructure, including planning aspects for the 2012 Olympic Games. "*As a result new strategies have been evolved and the potential of new materials in construction identified"*, states QinetiQ.

(e) Increasing productivity in the oil industry

Between 2008 and the present day, QinetiQ has been working with oil-extraction companies to improve yields from oil wells. QinetiQ notes that "*In many oil wells only 50% of the available oil is actually extracted, particularly in wells that exhibit low permeability. The main reason is because it is uneconomical and impractical to use standard perforation technologies, which are based on explosive shaped charges."* QinetiQ has used GRIM and its fundamental understanding of materials to develop a new perforator that increases the energy imparted to the rock above that offered by conventional perforator shaped charges; this has been achieved through the use of materials that react under shock loading. The higher energy results in significantly larger bore-hole volumes which, in tests by the company GEODynamics [F], have *"increased oil flow by 30-40%"*. QinetiQ add that *"The fundamental understanding of the behaviour of these reactive materials under shock loading and interpretation of experiments was only possible through the use of GRIM. This significantly shortened the R&D process, by approximately one half, the time to market and cost of the programme".* Additionally, QinetiQ *"has been able to licence the new perforator design* [G]*, which is now being extensively used by the industry, throughout the world, earning royalty fees and benefiting UK oil companies and the economy"*. These royalties comprise a "*significant fraction*" of the annual £4m income to QinetiQ's *Warhead Technology Group* (see quote in **§4a**); the exact fraction is commercially sensitive and has not been disclosed by QinetiQ.

(f) Informing expert witnesses

QinetiQ have used GRIM to inform expert witnesses in several high-profile inquiries, including the Lockerbie disaster, the Oklahoma bomb and the fatal Larkhall gas explosion. Although these predate the REF period, QinetiQ state that the GRIM study into the first of these "*resulted in the development of appropriate security strategies and the development of a 'bomb proof' liner for the luggage holds of short haul aircraft*": it is reasonable to assert that the impact of these two developments is both far reaching and, more importantly, has not only continued into the REF period, but will continue to do so beyond it.

5. Sources to corroborate the impact (snapshots of all URLs taken on 24th October 2013)

All sources are stored electronically and are available on request.

[A] (19th October, 2011) Email from "*Senior QinetiQ Fellow*" attesting to underpinning nature of Leeds research on QinetiQ's current capability.
[B] (11th June, 2013) Letter from "*Senior QinetiQ Fellow*" outlining end-user benefits.
[C] (11th June, 2013) Letter from "*Senior QinetiQ Fellow*" outlining and dating end-user impact.
[D] (14th June, 2013) Letter from (end-user) Dstl's "*Programme Leader, Weapons Domain*" endorsing the claims made in both this impact statement and the supporting statements [B,C].
[E] Corroboration of status of author of [A,B,C], who is the current President of the *International Ballistics Society*; see 2013 board of directors at http://www.ballistics.org/board_of_directors.php
[F] (a) PDF of 2010-12 GEODynamics ConneX® (main site http://www.perf.com/connex/) brochure, with proof of increased production revenue shown on page 8, which implies flow-rate increases of 50%, i.e. even better than those cited in [C]. (b) PDF of 2008 version of item [F] (a).
[G] (a) PDF of information on ConneX® reactive perforating shaped charge used by Weatherford International (main site http://www.weatherford.com) for oil extraction. (b) Video demonstrating benefits of new technology at http://www.youtube.com/watch?v=nrM4rrKhopY