Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 5. Successful Commercialisation of Advances in Computational Fluid Dynamics

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

Computational Dynamics Ltd, partnering with adapco and trading as CD-adapco www.cd-adapco.com is the world's largest independent CFD-focused provider of engineering simulation software, with major products STAR-CD and STAR-CCM+. It was formed by Professor David Gosman and Dr Raad Issa and its turnover has grown more than 30 fold since 1993 and by over 250% since 2008 to currently ~ $190M pa. It employs around 750 staff, of whom roughly 80 are located in the London office. The company won a Queen's Award for Exports in 1997. Key technologies that underpin this growth were developed since 1993 in the Mechanical Engineering department at Imperial College. CD-adapco has over 7000 users of its software, working at 3000 different companies. It makes a major contribution in maintaining the competiveness of UK industry via improved understanding and design and lower costs through the reduced need to undertake expensive experimental studies.

2. Underpinning research (indicative maximum 500 words)

CD-adapco was formed in 1987 by Professor David Gosman FREng and Dr Raad Issa, both members of the Mechanical Engineering department. The company's first product was STAR-CD, produced in 1987 and largely based on CFD technologies developed at Imperial. Some of the key early features were: body-fitted and moving meshes, implicit solution finite-volume solution algorithms and liquid fuel spray, turbulent combustion and radiation heat transfer models. Elements of this technology were also subsequently adopted by the other major CFD companies. ***This case study is solely concerned with code developments based on Imperial research post 1993.***

Imperial research was a vital input to the company in the post-1993 period, the key academic staff involved being Professor Gosman and Dr Issa. Professor Gosman was on the full time academic staff from pre-1993 until 2004; he was then half time for 18 months, since when he was a senior research investigator paid an honorarium until 2008 and then a distinguished research fellow (unpaid, but regularly in the department) to the present. Dr Issa was on the full time staff from 1993-2003 and has been a senior research investigator paid an honorarium since then. Particularly important developments occurred in the post-1993 period, the most significant of which was the unstructured-mesh methodology [1] that is applied in both the STAR-CD and the newer STAR-CCM+ code. This was a key enabler for addressing the full geometrical complexities of real industrial applications using automatic meshing techniques developed within the company and provided a significant competitive advantage. Further benefits were gained from the adaptation within this framework of the highly efficient PISO algorithm [2], which was particularly advantageous for unsteady flow applications. An overview of these and other novel developments is given in [3]. [4] describes the outcomes of a systematic programme of research at Imperial on the prediction of reciprocating engine combustion, including, post-1993, the introduction of moving unstructured meshes and advanced modelling of the processes of: fuel spray injection, wall impingement and wall film formation, spark and compression ignition, and petrol and Diesel combustion and pollutant emissions. This work has contributed to STAR-CD's reputation as the leading CFD code for engine simulation. Multiphase flow modelling was another Imperial research area and Ref 5 presents a powerful method for multiphase flow simulation allowing resolution of the phase interface topology, which has provided another competitive edge for both STAR-CD and STAR-CCM+.

A separate, unique and important strand of research during this period, described in Ref 6, looked at the viability of using an object-oriented programming language, C++, for CFD and other CAE applications. There were well-known advantages with this in terms of ease, reliability and flexibility of programming, but concerns about possible substantial computing time penalties relative to the widely-used FORTRAN language. A research C++ code called FOAM was written and tests

demonstrated that if best practices were used, no appreciable time penalties occurred. This led directly to the use of C++ in the production of the new flagship product STAR-CCM+, with attendant benefits.

3. References to the research * References that best indicate quality of underpinning research.

*[1] S. Muzaferija, A.D. Gosman, "Finite-volume CFD procedure and adaptive error control strategy for grids of arbitrary topology", Journal of Computational Physics, Vol 138, pp. 766-787, (1997) (Article number CP975853) http://dx.doi.org/10.1006/jcph.1997.5853

[2] P.J. Oliveira, R.I. Issa, "An improved PISO algorithm for the computation of buoyancy-driven flows", Numerical Heat Transfer Part B-Fundamentals, Vol 40, pp. 473-493 (2001) DOI

*[3] A.D. Gosman, "Developments in industrial computational fluid dynamics", Chemical Engineering Research & Design, Vol 76, Part A, pp. 153-161 (1998) DOI

[4] A.D. Gosman, "State of the Art of Multi-Dimensional Modeling of Engine Reacting Flows" Oil & Gas Science & Technology - Rev de l'IFP, Vol 54, Issue 2, pp.149-159, (1999) DOI

*[5] O. Ubbink, R.I. Issa, "A method for capturing sharp fluid interfaces on arbitrary meshes", Journal of Computational Physics, Vol 153, pp. 26-50, (1999) DOI

[6] H.G. Weller, G. Tabor, H. Jasak, C. Fureby, "A tensorial approach to computational continuum mechanics using object orientated techniques", Computers in Physics, Vol 12, Issue 6, pp. 620 - 631, (1998) DOI:10.1063/1.168744 **(Weller and Tabor were Mechanical Engineering postdocs at Imperial and supervised by Professor Gosman)**

4. Details of the impact

This case study concerns the impact of Imperial College research since 1993 on the CFD codes marketed by CD-adapco. The company has grown steadily over this period; its turnover has grown more than 30 fold since 1993 and by over 250% since 2008 to currently ~ $190M pa [A]. Its principal offices are located in London, Nuremburg and New York and it has numerous worldwide sales offices, for example in France, Germany, Italy, USA, Japan, Korea, China, India, Brazil and Russia. It employs nearly 750 staff of whom roughly 80 are located in the London office. The company won a Queen's award for exports in 1997. The impact of CD-adapco's CFD products STAR-CD and STAR-CCM+ is wide-ranging and of considerable benefit to UK and worldwide industries, by improving competitiveness via substantially reducing the costs and time for product development and enabling innovative design. Indeed, one of the key selling points of these products is the ability to offer a substantial return on investment through these savings.

STAR-CD, the original general-purpose code is now a bespoke internal combustion engine simulator, where it is undoubtedly the world 'number one'. It is used by most major manufacturers including Audi, BMW, Chrysler, Fiat, GM, Jaguar Land Rover, Hyundai, Lotus, Mercedes, Nissan, Renault, Toyota, Volkswagen and Volvo e.g. [7]. Mercedes, Ferrari and Renault also use it extensively in Formula 1 for engine design. Successful though this product was, it became apparent in the late 1990s that due to its age and architecture it was not a suitable platform to accommodate the improvements and expansions into new application areas that CD-adapco wished to make and also to exploit recent research advances at Imperial. Accordingly, it was decided to develop an entirely new general-purpose code, STAR-CCM+; and to specialise STAR-CD for reciprocating engine applications.

STAR-CCM+, first released in 2004, is the company's current flagship general-purpose CFD code, that also has electromagnetic, electrochemical and stress analysis capabilities. It is employed worldwide by a large number of companies in a very wide range of industries, e.g. aerospace (airplanes, rockets, UAVs [8]and [9], batteries/battery-powered equipment [10], chemical process, defence, food processing [11], fossil-fuelled and renewable (nuclear [13] and wind/solar) energy, electronics cooling [13], ground transportation (cars [12], trucks, trains), marine (ships, offshore structures [15], oil/gas production and processing [16], pharmaceutical, etc. The CFD software

market is extremely competitive and there is a continuing need to develop more powerful and flexible numerical solution techniques and new and improved models for a variety of physical phenomena. Developments in these areas at Imperial have assisted in CD-adapco maintaining a competitive edge throughout the lifetime of the company. This has been particularly true during the past two decades of rapid growth, due to the following:

- Implementation in both codes of the unstructured mesh methodology, including the associated numerical solver extensions [1, 2]. These have endowed both STAR-CD and STAR-CCM+ with fast transient solution and unique and powerful complex-geometry-handling capabilities that, when combined with automatic mesh generation methodology developed by the company, offer decisive advantages over the competition in terms of speed, capability and ease of use. In particular, it is no longer necessary, as in other codes, to simplify complex geometries in order to mesh and perform a CFD flow solution; and the mesh generation times are typically faster by an order of magnitude. Examples of the degrees of complexity that can be handled are shown in [3], [8], [12] and [13]. The additional benefits to STAR-CD of improvements of engine physics modelling at Imperial are described and illustrated in [4] and [7].
- Exploitation in producing the new-generation STAR-CCM+, of the proven advantages described in Ref 6 of the object-oriented C++ programming language. The first version of this code was released in 2004. In addition to the benefits of being easier to develop and maintain, the object-oriented architecture has facilitated the introduction of some novel features including multi-physics and CAD-to-results capabilities. The former comprises additional solid stress, electrochemistry [10] and electromagnetic solvers, which can be applied either individually or in a fully-coupled fashion with one or more of the others – for example, to perform fluid/structure stress and/or thermal interaction simulations. The latter feature refers to the ability of STAR-CCM+ to: (a) import or generate, using an internal solid modeller, a CAD description of the application geometry; (b) repair any defects in the description and isolate the fluid volume on which the analysis is to be performed; (c) automatically mesh this volume; (d) perform the required CFD and/or other physics analysis; and (e) manipulate, display and output the results in the desired form. Example applications are shown in [3], [8], [12] and [13] among others. STAR-CCM+ is unique in offering these features in a single code, as compared with the multiple code offerings of other CFD companies.
- Implementation in both codes of the multiphase flow methodology developed at Imperial, notably the free surface capturing technique [5] which has been particularly attractive to the marine and oil and gas industries, the former for ship design and the latter for offshore structures [15], pipelines and separation equipment [16].

The growth outlined above means that since 2008 there has been significant on-going impact underpinned by the research. The benefits of all of these developments are collectively reflected in the general-purpose STAR-CCM+ code, which has attracted favourable comments from many users. For example, in relation to the unstructured mesh and expanded modelling features, the Chief Engineer at Atkins [B], one of the world's leading design, engineering and project management consultancies, states that: *"The powerful geometry-handling capabilities of STAR-CCM+, together with its wide range of physics models, make it an ideal tool for the diverse applications we have to deal with."* These same features, together with the all in one CAD-to-results architecture facilitated due the use of C++, have been especially valued by the automotive community, where in a number of application areas they have enabled testing to be substantially reduced or even replaced by simulation, as reflected in the following remarks by Suwhan Kim, a senior engineer at Hyundai Motor Corporation in South Korea: *"The automation of underhood cooling performance analysis is a breakthrough in the field of automated systems. At Hyundai, thermal flow design engineers are very satisfied with the module [STAR-CCM+]. It has allowed them to cut down the preparation and design time by about 70%, and has shown no particular difficulty in simulating the overall cooling performance for the diverse range of Hyundai-Kia automobile models."* [17].

In Formula 1 where speed of turnaround is also important, the Head of CFD at Lotus Renault GP Limited [C] comments: *"The first thing that separates CD-adapco from the competition is STAR-*

CCM+: it's a state-of-the-art CFD code and since we introduced it we have managed to massively increase our simulation throughput. STAR-CCM+ is a massive step forward. The code itself is fast, robust and extremely easy to use so people new to the software can pick it up very quickly."

It is also particularly noteworthy that over the past 5 years the CD-adapco group turnover has increased by more than 15% per annum, a remarkable achievement in times of economic hardship and directly attributable to the substantial and proven return on investment which CD-adapco products offer, due to their unique features.

5. Sources to corroborate the impact

Publications relating to CD-adapco products

7. Y. Mito, K. Tanzawa, M. Watanabe, and Y. Eiyama, *"Advanced Combustion Performance for High Efficiency in New I3 1.2L Supercharged Gasoline Engine by Effective Use of 3D Engine Simulation,"* SAE Technical Paper 2012-01-0422, (2012). DOI: 10.4271/2012-01-0422.
8. A. Egolf and M. Dombroski, *"Sikorsky Aircraft Predicts Drag of Production Hub Geometries Using CFD"* Dynamics Issue 34 (2013) http://www.cd-adapco.com/teaser/sikorsky-aircraft-predicts-drag-production-rotor-hub-geometries-using-cfd (Archived here on 5/09/13)
9. M. M. Grigoriev, C. V. Swiatek and J. A. Hitt *"Benchmarking CD-Adapco's Star-CCM+ in a Production Design Environment"* ASME Turbo Expo 2010, *Proc. ASME*. 44021, Volume 7: Turbomachinery, Parts A, B, and C 1019 (2010) DOI: 10.1115/GT2010-23627
10. S. Fell, E. Schneider, M. Lindner, R. Immel andJ. Kremser, *"Li-ion battery simulation strategies and validated implementations for the virtual development process of electrified vehicles",* SIMVEC – Berechnung, Simulation und Erprobung im Fahrzeugbau, VDI-Berichte 2169, p.241-254, (2012), ISSN 0083-5560, ISBN 978-3-18-092169-3; VDI Verlag GmbH, Düsseldorf
11. Hans-Jurgen Bitterman, *"CD-adapco Helps Tetra Pak Shorten Product Development and Implementation Times"* Dynamics Issue 34, (2013), http://www.cd-adapco.com/teaser/cd-adapco-helps-tetra-pak-shorten-product-development-implementation-times (Archived at here on 5/09/13)
12. H. Reister. and W. Bauer, *"Simulation Process of the Heat Protection of a Full Vehicle,"* SAE Technical Paper 2012-01-0635, (2012), DOI: 10.4271/2012-01-0635.
13. J. Yan, B. Kochunas, M. Hursin, T. Downar, Z. Karoutas and E. Baglietto *"Coupled Computational Fluid Dynamics and MOC Neutronic Simulations of Westinghouse PWR Fuel Assemblies with Grid Spacers"* Proc 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH14-254, (2012)
14. Sergei Shulepov, *"Philips Stays Cool With CD-adapco"* CD-adapco Electronics Special Report, (2011), http://www.cd-adapco.com/teaser/philips-stays-cool-cd-adapco (Archived here on 5/09/13)
15. Harald Ottens, Radboud van Dijk and Geert Meskers *"Benchmark Study Between CFD and Model Tests on a Semi-Submersible Crane Vessel"* ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering" Paper No. OMAE2009-79749, (2009); DOI: 10.1115/OMAE2009-79749
16. Stephen Ferguson and Douglas Lee, *"Forever Blowing Bubbles – Revolutionary MBF™ Separator Design With CFD"*, CD-adapco Energy Special Report,(2011), http://www.cd-adapco.com/teaser/forever-blowing-bubbles (Archived here on 5/09/13)
17. Su-Whan Kim and Ghuiyon Kim, *"Combining Automation With Scalability: Hyundai's Innovative Underhood Cooling Analysis Module"* Dynamics Issue 34, (2013), http://www.cd-adapco.com/teaser/combining-automation-scalability-hyundais-innovative-underhood-cooling-analysis-module (Archived at here on 5/09/13)

Sources to confirm the industrial impact

[A] Director, CD-adapco can supply audited accounts to confirm CD-adapco's growth

[B] Chief Engineer, Atkins Ltd confirms *STAR-CCM+* as an ideal tool for diverse applications

[C] Head of CFD, Lotus F1 Team to confirm that *STAR-CCM+* allowed them to massively increase simulation throughput.