Institution: University of Leeds

Unit of Assessment: 14 Civil and Construction Engineering

Title of case study: Case Study 4: Novel optimisation significantly reduces costs, increases turnover and reduces emissions.

1. Summary of the impact

Optimisation tools developed in the UoA have significantly advanced the ability to find the best designs for complex systems in cases where these were previously unobtainable. These optimisation tools have been implemented in several companies to shorten design times, reduce costs and reduce CO_2 emissions. This has brought about new multi-million pound revenues, long-term contracts, increased employment and contribution to sustainability targets.

2. Underpinning research

Since 2006 the UoA (Toropov**,** Polynkin) has developed and applied a range of optimisation methodologies that have enabled the wider use of optimisation in industry which in turn has delivered enhanced products and processes. This has focused on metamodelling and improved sampling.

Metamodelling-based optimisation and stochastic analysis are used in situations where even a single numerical simulation of a system or a complex process is not possible due to any of: excessive computing time; response polluted by numerical noise; instabilities in the calculations. These problems are exacerbated by the fact that an optimisation run or a Monte Carlo simulation requires many simulations rather than just one. In view of this the only realistic way of addressing such problems is to build high quality "emulators" or "metamodels" to mimic the full model. These (i) describe the behaviour of the system (or a process) with sufficient accuracy as compared to a full simulation, (ii) are computationally inexpensive and (iii) do not possess any significant amount of numerical noise. When such metamodels are obtained and, importantly, their quality is verified, they can be used in optimisation or a Monte Carlo simulation in place of the original, significantly more expensive simulations.

In order to build a metamodel it is necessary to perform **sampling** by running a sufficient number of numerical simulations in the space of optimisation variables and/or stochastic factors according to a carefully chosen design of experiments (DOE). Experiments normally refer to numerical simulation at various combinations of optimisation or stochastic variables, but research in the UoA demonstrated that this may also include laboratory experiments [1]. Uniform designs of experiments that are based on the concept of an optimal Latin hypercube have been developed in the UoA with the intention of gathering as much information on the behaviour of the system (or a process) as possible with a minimum number of sampling points thereby ensuring fidelity but with minimum computer time. These innovative methods include nested DOEs, i.e. individual uniform DOEs that are used separately for metamodel building and validation and can then be merged while remaining uniform [2]. This research was carried by Toropov at Leeds out in collaboration with Altair Engineering and Bradford University.

Key metamodelling techniques developed by Toropov and Polynkin include:

- Metamodel building using the concept of Moving Least Squares Method (MLSM) that is a technique flexible enough to describe the sampling data with high accuracy when the amount of numerical noise is small but also has the capability of filtering out numerical noise when it becomes an issue. This has been a basis for a multidisciplinary optimisation framework [3].
- Metamodelling, based on the interaction of low- and high-fidelity simulation models, that is beneficial for creating high quality metamodels when a lower complexity simulation model is available in addition to the original high fidelity simulation model. In such case the metamodel can be based on the low fidelity model which is corrected and tuned using only a small number of runs of the high fidelity model [4]. This research was done by Toropov in collaboration with

Hiroshima University.

Another major research outcome in the UoA has been the development of a large-scale optimisation technique (hundreds of design variables) based on the mid-range approximation method (MAM) utilising a trust region strategy. In order to deal with the "curse of dimensionality", approximations in MAM are based on the class of intrinsically linear functions and also include simple rational functions and moving least squares approximations with a linear base function. The final approximation is arrived at using an adaptive selection and regression-based model assembly [5]. This research in the UoA has been funded jointly by TSB, Rolls-Royce and Airbus.

Another aspect of fundamental research has been the development of the methodology for the composite optimisation of large scale structures. This optimisation problem is too large to be solvable by existing means and the optimisation method (developed by Toropov and applied by researchers from the School of Mechanical Engineering at Leeds) reduces this complexity to a manageable level [6]. This work was done within an EU FP-7 project ALaSCA.

The techniques described here give a suite of optimisation techniques that have been applied by the University of Leeds to a wide range of applications which have generated significant impacts some of which are set out in Section 4.

Key researchers in this work were:

1. Vassili Toropov, Professor: 01/04/2006 - present.
2. Andrey Polynkin, Research Fellow: 17/04/2007 - 30/11/11

Researchers outside the UoA were:

1. Harvey Thompson, School of Mechanical Engineering: Research Fellow, 1995-2000; Lecturer, 2000-04; Senior Lecturer 2004-11; Professor, 2011-present.
2. David Barton, School of Mechanical Engineering: Professor, 01/01/85 to date.
3. Osvaldo Querin, School of Mechanical Engineering: Lecturer, 13/6/2000 – 31/7/03; Senior Lecturer, 1/8/03 – 1/10/12, Associate Professor, 1/10/12 – present.

List of key awards that supported the above research (amounts are the University of Leeds share):

EU:

- AMEDEO (Aerospace Multidisciplinary-Enabling Design Optimisation), £701,444, 2012
- ALASCA (Advanced Lattice Structures for Composite Airframes), £170,228, 2011.

Parker Hannifin:

- Design of Super-impactors, £377,431, 2009.

TSB:

- SILOET-II, £256,001, 2013.
- EADS UK Ltd. KTP, £163,615, 2010.
- Airbus IM KTN, £14,950, 2011.

3. References to the research

[1] Vu, H.M., Forth, J.P., Dao, D.V. and **Toropov, V.V.** The use of optimisation for enhancing the development of a novel sustainable masonry unit. Appl. Math. Modelling, DOI: 10.1016/j.apm.2013.07.026

[2] Narayanan, A., **Toropov, V.V.**, Wood, A.S. and Campean I.F. Simultaneous model building and validation with uniform designs of experiments. Engineering Optimization, 39(5): 497-512, 2007, DOI: 10.1080/03052150701399978

[3] Zadeh, P.M., **Toropov, V.V.** and Wood, A.S. Metamodel-based collaborative optimization framework. Structural and Multidisciplinary Optimization, 38, 103–115, 2009, DOI: 10.1007/s00158-008-0286-8

[4] Hino, R., Yoshida, F. and **Toropov, V.V.** Optimum blank design for sheet metal forming based on the interaction of high- and low-fidelity FE models, Archive of Applied Mechanics, 75(10-12): 679-691, 2006, Invited paper for the special issue on the 75th anniversary of the journal, DOI: 10.1007/s00419-006-0047-3

[5] **Polynkin, A.** and **Toropov, V.V.** Mid-range metamodel assembly building based on linear regression for large scale optimization problems. Structural and Multidisciplinary Optimization, 45 (4): 515-527, 2012, DOI: 10.1007/s00158-011-0692-1

[6] Liu, D., **Toropov, V.V.,** Querin, O.M. and Barton, D.C Bilevel optimization of blended composite wing panels. AIAA Journal of Aircraft, 48(1): 107-118, 2011. DOI: 10.2514/1.C000261

*Note: Authors from the University of Leeds in **bold**. The three papers selected to demonstrate the quality of the underlying research are [3], [5] and [6]. They are published in internationally-recognised leading journals and have attracted significant interest through citation and take-up by other researchers.*

4. Details of the impact

Parker Hannifin

The metamodel-based optimisation methods developed in the UoA and described in Section 2 have been combined with high fidelity Computational Fluid Dynamics analysis (Thompson, School of Mechanical Engineering, University of Leeds) to develop new product design optimisation software [A, B, C]. A transformation of the design variable space was proposed that has dramatically improved the fidelity of the metamodel without an excessive number of CFD simulations thus providing a practical tool for the pump designers [A].

Based on research in the UoA the company developed software which they then used to increase the efficiency of their jet pumps by 20% [A]. From 2010 this optimisation software was applied to the new Racor Super Impactor crankcase ventilator to reduce engine emissions in line with Euro 6 requirements and boost fuel efficiency [A]. This new component of diesel filtration systems was awarded the prestigious Grand Prix prize at the 2012 British Engineering Excellence Awards: “An inventive engineering solution that solves a significant environmental problem and which has strong commercial drivers to a large potential market” [D].

This innovation based on research described in Section 2 has enabled the company to secure a number of orders from major clients, thereby creating 80 new jobs [A]. The company has further used this new product to gain new business from a key manufacturer in the agriculture and construction machines sector. This contract, worth £1.5 million per year (2012-2017), has led the company to appoint nine new employees to deliver the new business [A]. The company has further stated that “the research is having a major influence on the company’s current strategy and growth plans; the company expects that its engagement with Leeds will directly lead to a further £3 million revenue per year by 2013/14, growing to £10 million per year by 2015” [A].

Yorkshire Ambulance Service NHS Trust

The Yorkshire Ambulance Service (YAS) provides emergency services to people across Yorkshire and their fleet of vehicles travel 40 million kilometres each year. YAS has over 110 locations, 4500 staff and 1500 vehicles. Having participated in the Carbon Trust’s Public Sector Carbon Management programme in 2010, YAS drew up a Carbon Management Plan for 2011-2015. Taking 2007 as the baseline year when the carbon footprint was 16,531 tonnes of CO_2, YAS decided to set a target of a 30% reduction in carbon usage by 2015 with the added benefit of a cost saving of £3.39 million.

Researchers in the UoA secured an EPSRC Knowledge Transfer Secondment (EP/H500251/1) which allowed them to work with YAS in applying the optimisation research described above to ambulance design in conjunction with Computational Fluid Dynamics from the School of Mechanical Engineering at Leeds (Thompson). Initial investigation led to a focus on the light bars on the vehicle roof and this demonstrated that the drag force could be reduced by up to 20% [E].

This optimised design was applicable to up to 60% of the YAS fleet which was shown to equate to an annual £700,000 saving in fuel costs and an annual reduction of 500 tCO_2 [E].

Based on the results of the KTS YAS commissioned new ambulance designs that came into operation in early July 2013 [E]. The new vehicles have achieved 26 mpg compared to 16-18 mpg previously [E]. Given the figure of 40 million kilometres per year across the YAS fleet this equates to significant potential savings. YAS state "in the first year of utilising the new vehicles in part of the fleet YAS expect to save £300,000 in fuel" along with the consequent CO_2 reductions [E].

Rolls-Royce

The research on optimisation outlined above has been implemented in the Rolls-Royce SOFT optimisation system leading to its successful use during the REF period "in live aeroengine design projects with tens of hours of CPU time per simulation and over a hundred design variables" [F]. In this way the research in the UoA has led to optimisation of designs that was previously impossible due to prohibitive computational requirements [F].

Rolls-Royce states that the systems based on the UoA research "has been successfully used for real-life optimisation of RR compressor blades (e.g. the ESS (Engine Sector Stator blade) component of a high-bypass ratio engine) and on the Trent turbine HP and IP stages that are being developed in RR". Through using the MAM outlined in Section 2 Rolls-Royce have seen a reduction in CPU time of an order of magnitude and significantly improved performance in handling near equality constraints [F]. Ultimately this has led to "0.15% efficiency improvements of critical components like IP (Intermediate Pressure) Turbine stages of a modern high by-pass jet engine" in the REF period [F].

Rolls-Royce has used the SOFT optimisation system on a number of other design projects for turbomachinery. Whilst the Rolls-Royce system has a range of optimisation techniques, Rolls-Royce states that "so far, MAM has proved to be the most efficient and accurate of the optimisers where expensive high fidelity CFD codes are used in the optimisation process" [F] and that "overall MAM has been an order of magnitude faster than other previously used techniques, this has reduced the optimisation time significantly, and made MAM a practical design tool on a modest Linux cluster" [F].

It is hard to put a financial figure to these benefits and Rolls-Royce do not calculate such figures due to the uncertainties of operating conditions and other variables. However, given that a commercial airline spends billions of dollars per year on fuel [G], even a small efficiency improvement leads to millions of dollars of cost savings.

5. Sources to corroborate the impact)

A. Individual written corroboration (October 29th, 2013) from Research and Development Manager, Parker Hannifin Manufacturing (UK) Ltd, Filter Division Europe, Churwell Vale, Dewsbury, WF12 7RD.
B. Eves, J., Toropov, V.V., Thompson, H.M., Kapur, N, Fan, J., Copley, D. and Mincher, A. Design optimization of supersonic jet pumps using high fidelity flow analysis. Structural and Multidisciplinary Optimization, 45 (5): 739-745, 2012, DOI: 10.1007/s00158-011-0726-8.
C. Fan, J., Eves, J., Thompson, H.M., Toropov, V.V., Kapur, N., Copley, D. and Mincher, A. Computational fluid dynamic analysis and optimization of jet pumps. Computers and Fluids, 46: 212–217, 2011, DOI: doi:10.1016/j.compfluid.2010.10.024.
D. British Engineering Excellence Awards: http://www.beeas.co.uk/winners/beeas-2012-winners.pdf (accessed August 28th, 2013; see page 3).
E. Individual written corroboration (October 17th, 2013) from Environmental and Sustainability Manager, Yorkshire Ambulance Service NHS Trust, Brunel Road, Wakefield 41 Business Park, Wakefield, WF2 0XG.
F. Individual written corroboration (October 24th) from Engineering Associate Fellow - Aerothermal Design System, 3D Geometry, Meshing and Optimisation Team Lead, Rolls Royce plc., Derby.
G. British Airways Annual Report and Accounts 2012: http://www.iairgroup.com/phoenix.zhtml?c=240949&p=irol-reportsannual (accessed August 28th, 2013, see page 6).