Institution:	The University of Liverpool
Unit of Assessment:	UoA12 Engineering
Title of case study:	Enhanced virtual engineering reduces development times in Nuclear and Aerospace Industries
Period when the underpinning research was undertaken:	2008-2019

Details of staff conducting the underpinning research from the submitting unit:

Names(s):	**Roles(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
JE Mottershead	Professor	1995 – present
EA Patterson	Professor	2011 – present
CM Sebastian	Lecturer	2015 – 2017

Period when the claimed impact occurred: 1st August 2013 – 31st July 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

The advance made in Liverpool is technology for quantitatively comparing fields of data acquired in the real and virtual worlds during a system's lifecycle. This has led to closer integration of physical tests and simulations of aircraft structures, resulting in fewer data-rich tests being conducted by aerospace organisations and reducing development times by 30% with savings of GBP10,000,000 per development cycle. The technological approach has also been implemented in an integrated nuclear digital environment (INDE) with cost savings of 20-40% during a powerplant's lifecycle; and a reduction of 20 years in the project timeline for the Spherical Tokamak for Energy Production (STEP).

2. Underpinning research

Introduction: The use of computational models has become ubiquitous for design optimisation and evaluation of the integrity of engineering components and structures. The conflicting demands for components and structures that are sustainable, reliable and low-cost, drives the need for elegant designs and requires engineers to have very high levels of confidence in their computational models. Model validation is a crucial step in establishing this confidence. The development of industrially-applicable and internationally-acceptable validation methodologies was the motivation for a pair of EU Framework 7 projects, ADVISE (Advanced Dynamics Validations via Integrated Simulation & Experimentation (2008-2011)) for which Mottershead was Liverpool PI and VANESSA (Validation of Numerical Simulations: Standardisation Actions (2012-2014)) for which Patterson was Liverpool PI. Patterson was technical coordinator of both ADVISE and VANESSA; and moved to Liverpool in 2011 supported by a Royal Society Wolfson Research Merit Award. These projects led directly to a pre-standard CWA16799:2014 on 'Validation of computational solid mechanics models' published by Comité Européen de Normalisation (CEN) [5.1].

The challenge addressed in the ADVISE project was to create an effective method of quantitatively comparing predicted and measured surface strain fields in engineering components and structures. Together Mottershead and Patterson, with their PhD students, Weizhuo Wang and Chris Sebastian, developed the concept of treating maps of surface strains for components as images that can be decomposed and represented by feature vectors, i.e. a reduction from arrays of tens of thousands of values to less than 100 values [3.1]. The appropriate design of the decomposition process ensures that the feature vector is unique and allows it to be invariant to rotation, scaling and translation of the image. These properties enable feature vectors to be used for straightforward statistical comparisons of the strain maps that they represent. The facility to make statistical comparisons has underpinned three pieces of research by Patterson's team in Liverpool: first, in 2013, the creation of a methodology for model validation [3.2] that forms the core of the CEN pre-standard (CWA16799:2014) [5.1]. Second, the development of a strain-based approach to damage detection in components, which was only fully published in 2019 [3.3]. And, in a final step in ADVISE, these two developments were integrated with quality assurance procedures to develop the concept of a strain continuum extending over a system's life-cycle [3.4]. This underpinning research was a key enabler for virtual testing of aircraft structures and in the creation of an integrated nuclear digital environment (INDE), as proposed by Patterson and his colleagues at the National Nuclear Laboratory [3.5].

Critical to interpretation of these statistical comparisons is knowledge of the minimum measurement uncertainty, because differences between data fields that are larger than this uncertainty are likely to be significant. The ADVISE project also developed standard calibration methods for quantifying the minimum measurement uncertainty in deformation fields [3.6] using novel reference materials (EU Design Registration 000213467). These calibration methods were incorporated in the CEN Workshop Agreement (CWA16799:2014), which was prepared in collaboration with representatives from the aerospace, automotive, instrumentation, nuclear power, and space industries [5.1].

3. References to the research

[3.1] Wang W, Mottershead JE, Sebastian CM & Patterson EA, Shape features and finite element model updating from full-field strain data, *Int. J. Solids Struct*. 48(11-12), 1644-1657, 2011. DOI:10.1016/j.ijsolstr.2011.02.010

[3.2] Sebastian C, Hack E & Patterson EA, An approach to the validation of computational solid mechanics models for strain analysis, *J. Strain Analysis*, 48(1):36-47, 2013. DOI:10.1177/0309324712453409

[3.3] Middleton CA, Galo A, Greene RJ & Patterson EA, Towards automated tracking of initiation and propagation of cracks in aluminium alloy coupons using thermoelastic stress analysis, *J. Nondestructive Evaluation*, 38:18, 2019. DOI:10.1007/s10921-018-0555-4

[3.4] Patterson EA, Feligiotti M & Hack E, On the integration of validation, quality assurance and non-destructive evaluation, *J. Strain Analysis*, 48(1):48-58, 2013. DOI:10.1177/0309324712444681

[3.5] Patterson EA, Taylor RJ & Bankhead M, A framework for an integrated nuclear digital environment, *Progress in Nuclear Energy*, 87:97-103, 2016 DOI:10.1016/j.pnucene.2015.11.009

[3.6] Hack E, Lin X, Patterson EA & Sebastian CM, A reference material for establishing uncertainties in full-field displacement measurements, *Measure. Science &Technology*, 26:075004, 2015.DOI:10.1088/0957-0233/26/7/075004

4. Details of the impact

The enabling technology is the capability to quantitatively compare fields of data acquired in the real and virtual worlds. Then, to make these quantitative comparisons throughout a system's lifecycle within a digital environment [3.4]. This includes model validation during product development [3.2], quality assurance during manufacturing, and condition-monitoring during service [3.3]. The new approach to model validation is described in a CEN pre-standard published in 2014 [CWA16799:2014],[5.1] which followed directly from research in Liverpool supported by the EU Framework 7 projects, ADVISE and VANESSA. Although widely applicable, the main impacts have been in the aerospace and nuclear sectors.

Aerospace sector

In the aerospace sector, this technology is an enabler for the virtual test approach being pioneered by Airbus to reduce development times and costs for aircraft structures. Virtual testing integrates a very small number of physical tests with computer simulations. The new approach is being implemented by Airbus using: (a) the advances in comparing strain fields [3.1] to develop robust validation protocols for computation models [3.2]; and, (b) the damage-tracking technology [3.3] to continuously monitor the condition of structures under test. For example, the damage-tracking technology, developed at Liverpool, was applied on an A330 Side-Stay test at Airbus in Filton during 2018, where it allowed the test to be completed in less than a year instead of the typical 2 to 3 year duration and saved GBP9,000,000 in this specific case. A Structures Test expert at Airbus said:
'Calibrated full-field measurement techniques, made possible by Liverpool's validation toolkit, are progressively replacing single-point strain measurement techniques, saving approximately GBP10,000,000 over a development cycle' [5.2]

In Europe:

The Clean Sky 2 consortium of European aerospace companies recognised the potential for reductions in development times and costs; and invited bids to demonstrate applications of the technology. Consortia led by Patterson made two successful bids. First, MOTIVATE (Matrix Optimisation for Testing by Interaction of Virtual & Test Environments, 2017-2020) in which the new validation protocols have been demonstrated on a full-scale test on a cockpit in 2019 at Airbus in Toulouse, utilising strain field decomposition [3.1] for validation of computational models [3.2] and taking account of measurement uncertainties [3.6]. And second, DIMES (Development of Integrated MEasurement System, 2019-2020) which demonstrated the strain-based damage-tracking technology [3.3] on a full-scale wing test at Airbus in Filton in 2020. A Structures Test expert at Airbus said:
'In a change of policy, Airbus is deploying condition-led monitoring in its single-aisle airframe development project. Condition-led monitoring relies on the fully automated crack detection and monitoring techniques, developed with Liverpool. Adoption of this technology allows tests to be run 24/7, saving 3 months on each year-long test, directly supporting the company target to reduce the development cycle from 7 to 5 years.' [5.2]
These demonstrations have led to a change in policy at Airbus and a shift in culture with more than 50 Airbus engineers attending a series of internal annual workshops led by Patterson between 2018 and 2020.

In North America:

There is evidence of wider impact in the aerospace sector through additional R&D investment from the United States Air Force (2015-19) to support the development of model validation [3.1, 3.2, 3.4] for multi-physics models of failure modes in extreme environments associated with hypersonic flight; and separately, for damage detection [3.3] in high-performance ceramic-matrix composites (2017-19). Furthermore, the National Research Council Canada's Aerospace Research Center has adopted Liverpool's methodologies for their structural tests on aircraft and estimate that the tools for comparing test data with simulations has improved the efficiency of their tests, saving between 2 and 8 person-years annually. A Senior Research Officer at National Research Council Canada said:
"The Liverpool reference standard techniques are used for vetting new full-field measurements and identifying issues with the measurement system. This avoids re-running tests due to incorrect set-up or faulty equipment improving our test efficiency by 10-15%." [5.3]

Currently, the use of the Liverpool methodologies to quantify uncertainty and to correlate predictions with real-world data, are being embedded into a joint airframe manufacturing standard being developed by Airbus, Boeing, and Bombardier [5.2].

Nuclear power sector

The Integrated Nuclear Digital Environment (INDE), conceived by Patterson with colleagues at the National Nuclear Laboratory (NNL) in 2016 [3.5], has influenced research policy in the UK. INDE is a virtual framework in which computational predictions from multi-physics models and measurement data from the physical world can be integrated over the nuclear fuel cycle using the methods for quantitative comparison of data fields [3.1], for model validation [3.2] and for creation of data continua [3.4]. The former Chief Science & Technology Officer, NNL, said:
'INDE has created a sandpit to develop digital technologies which can be applied more broadly. The conversation that started with INDE has had an impact with NNL and its customers and has now widened to include Government and the Regulators' [5.4]

Fission Energy:

The INDE concept, developed in Liverpool, directly influenced UK Government policy via the Nuclear Industry Research Advisory Board's (NIRAB) recommendations. As a result, the GBP180,000,000 funded Nuclear Innovation Programme identified virtual engineering as a cross-cutting research theme. A consortium led by Wood plc (now Jacobs Engineering) with Liverpool, EDF Energy, NNL and Rolls-Royce was awarded the GBP3,600,000 Nuclear Virtual Engineering Capability (NVEC) programme that has created a proof of principle for INDE [5.4]. The principles are being applied in the Small Modular Reactor (SMR) and nuclear propulsion programmes led by Rolls-Royce. The Technology Manager of NNL said: '*Liverpool began working on disseminating ideas around digital twins for nuclear in 2014 and were one of the trailblazers of this technology concept before this took off later in 2016. One example of this is the Centre for Digital Built Britain. This body has been greatly influenced by the INDE concept, which has been embraced wholeheartedly with their vision for a national digital twin'* [5.4].
In tandem with his appointment at Liverpool, Patterson was the 2014 Hsue-Shen Tsien Professor of Engineering Sciences at the Chinese Academy of Sciences and established a collaboration with the Nuclear Power Institute of China (NPIC) that has led to a series of visits to and from Liverpool. In 2017, NPIC's parent organisation, the Chinese National Nuclear Corporation invested in a Nuclear Energy Software and Digital Reactor Engineering Technology Research Center [5.5] to advance its own work on INDE.

Decommissioning:

The principles are also being applied in Jacob's Integrated Innovation in Nuclear Decommissioning (IIND) project that is demonstrating a new approach to tackling decommissioning and dismantling of potentially contaminated cells on the Sellafield site; and by NNL in a digital decommissioning replica of the Magnox Swarf Storage Silo (MSSS). The implementation of the INDE principles in the digital replica for MSSS, reduced project uncertainties leading to savings calculated to be between GBP6,000,000 and GBP8,000,000 over the 25+ year lifetime of waste retrievals [5.4]. These developments are leading the UK civil nuclear industry towards the implementation of Industry 4.0, including the development of modular production, see for example 'Government Soft Landings' report [5.6]. Wood plc estimated that these changes in culture and practice will save up to 40% on design development, between 10 to 20% on construction, 30% on operation and 20 to 40% on decommissioning of nuclear power stations [5.7].

Fusion energy:
Patterson is working with the UKAEA on digitally enabled regulation of fusion power plants. The INDE principles are embedded in the Fusion Technology Facilities (FTF) programme, part of the GBP86,000,000 National Fusion Technology Platform funded by the UK government. The adoption of the INDE principles has reduced the project timeline by 20 years and eliminated millions of pounds of test costs from the GBP220,000,000 Spherical Tokamak for Energy Production (STEP) programme to construct a commercially-viable fusion power station. The STEP Delivery Director, UKAEA said:
'If we were to do STEP in the traditional sense (without INDE), where we make full mock-ups with full-scale testing, the timescales would be delivery in the 2060s, rather than 2040' [5.8].

5. Sources to corroborate the impact

[5.1] CEN Workshop Agreement on Validation of Computational Solid Mechanics Models, CWA 16799, Comité Européen de Normalisation, Brussels, 2014 Available at https://www.empa.ch/documents/1583244/0/CWA+16799/0b7cc516-30a3-46df-aa9d-95bf32f7b6bd.

[5.2] Letter and accompanying documentation from Structures Test Expert at Airbus in Toulouse describing impact of research by Patterson's group on testing strategy and development times and costs for aircraft structures at Airbus. Quoted text p7.

[5.3] Letter and accompanying documentation from Senior Research Officer, at National Research Council Canada confirming their use of technology derived from the group in Liverpool and confirming its impact on the efficiency of their tests. Quoted text p5.

[5.4] Letter from Head of R&D, National Nuclear Laboratory confirming influence of Liverpool research on civil nuclear industry. Quotes from p1 and p3.

[5.5] Evidence of change in culture in civil nuclear industry in China http://en.cnnc.com.cn/pdf/AppealingNuclearPowerBeautifulChina.pdf (see p.5, 29 & 32).

[5.6] Evidence of change in culture in civil nuclear industry in the UK: Isgar P, Elsden A & Bew M, Building information modelling and data management: nuclear strategy, Government Soft Landings, Construction Industry Council/Cabinet Office/BIS, Feb. 2016 http://www.waldeckconsulting.com/wp-content/uploads/2016/06/BIM_Nuclear_Strategy_v10pdf.pdf

[5.7] Aslam A, Kyrieleis A, Collaborative use of nuclear virtual engineering capability – estimates of cost savings, Wood plc, Report no. 207134-0000-DP00-MEMOO-001, 28th November 2018.

[5.8] Letter and accompanying documentation from STEP Delivery Director confirming the influence of research by Patterson's group on development of STEP project. Quoted text p2.