Institution: Swansea University		
Unit of Assessment: 12		
Title of case study: Improved modelling capability for aerospace and other industries through application of an unstructured mesh technology.		
Period when the underpinning research was undertaken: 2003 - Present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Kenneth Morgan Oubay Hassan Ben Evans	Professor Professor Associate Professor	1975-1989; 1991-Present 1994-Present 2012-Present
Period when the claimed impact occurred: 2014 - Present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

FLITE, a computational aerodynamics design system developed by Swansea University (SU) researchers, has been of significant economic benefit to the aerospace and other industries. Significant enhancements to the computational fidelity and robustness of the system, coupled with its High Performance Computing (HPC) platform implementation, enabled its use for highly complex modern industrial aerospace configurations. The various modules of the FLITE system have been utilised by several international organisations and companies, including Airbus, the Institute of High Performance Computing (IHPC; Singapore) and WebSim Ltd. generating tens of millions of UK pounds of economic impact. Its use in the design of the BLOODHOUND Supersonic Car (SSC) has also contributed to significant public engagement in science and engineering through a large-scale education programme with which over 6,000 schools have engaged.

2. Underpinning research

In the last two decades, computer modelling has become an integral part of industrial design. The use of unstructured grid technology has enabled the use of finite element and finite volume techniques for the flow and structural analysis of realistic complex industrial geometries. This advancement in computer modelling required the development of robust unstructured 3D mesh generation techniques capable of creating appropriate grids for an accurate simulation.

The successful Swansea University unstructured grid system, FLITE, was initially developed to model compressible aerodynamic flows. The system contains an automatic mesh generation capability for arbitrary geometries. The basic mesh generator, representing a significant advance in this area, was based upon Delaunay isotropic triangulation, with automatic point creation. The international significance of this work led to further mesh generator enhancements, undertaken in a series of EU, EPSRC and industry-funded research projects **[G1, G2, G3, G4]**, providing improved functionality, robustness and efficiency for real aerodynamic geometries. This included the ability to generate highly anisotropic hybrid meshes in the vicinity of solid walls, to capture the severe boundary layer gradients at high Reynolds number, enabling the simulation of Reynolds-averaged Navier–Stokes (RANS) models on industrial geometries **[R1]**. A metric-based, anisotropic Delaunay triangulation was also developed to ensure that the generated meshes could be tailored to geometric features and could use adaptivity to efficiently capture important flow features **[R2]**.

These enhancements were later implemented within the Airbus meshing suite that is used within their aircraft design cycle. Also incorporated within the Airbus meshing tools were parallel implementations of the FLITE meshing process and a process of the mesh adaptivity for unsteady flows with moving boundary components **[R3, R4]**. A number of these techniques were later integrated in the Solar CFD (computational fluid dynamics) System

(https://www.ara.co.uk/services/computational-aerodynamics/cfd-software-code-development/), developed by the Aircraft Research Association (ARA), and used by BAE Systems, for the modelling of complex aerodynamic geometries of industrial interest. The complete meshing system was recently adopted by a Swansea University spin out company, WebSim, specialising in developing an on-demand online modelling simulation environment.

The computational performance of the basic FLITE system has also been further improved. The addition of an artificial compressibility approach, with an implicit dual time stepping scheme, enabled the simulation of incompressible flows. The computational performance was enhanced by the incorporation of multigrid acceleration and by parallelization of the solution algorithm **[R1]**. The simulation of general time dependent turbulent flows, involving geometries that change in time, was facilitated by the introduction of a capability that ensured geometric conservation on hybrid meshes **[R5]**.

The SU advanced meshing research and system, together with the above-mentioned added functionalities formed the basis of the software that was adopted by the IHPC in Singapore in 2008 and it is now the workhorse in their Fluid Dynamics Unit **[G5]**.

EPSRC funding **[G6]** led to further enhancement of the FLITE system, enabling the simulation of a supersonic vehicle moving over soft ground. These improvements included the incorporation of a more sophisticated two-equation turbulent flow model, the ability to simulate rotating flow and a staggered technique to model spray drag. As wind tunnel testing cannot accurately model the interaction between a moving vehicle and the ground, the aerodynamic design of the BLOODHOUND Supersonic Car (SSC), a vehicle intended to achieve speeds beyond 1,000 mph, was undertaken using this enhanced FLITE computational aerodynamics system. The computational model developed was validated in November 2019 by comparing FLITE predictions with results obtained during initial testing of the SSC on the Kalahari Desert. In this testing, the vehicle safely achieved a speed of 635 mph **[R6]**.

3. References to the research

The outputs below include five peer-reviewed journals (all of which are in JCR Q1 or Q2), and one peer-reviewed conference paper at a well-established international conference. Three of the papers were written with industrial collaborators such as EADS, MathWorks and the Bloodhound Project. Funders including EPSRC, and the EU support two of the journal articles. Six grants (majority of which are competitively won) support the body of work totalling GBP2,153,405. This research has made important contributions to the discipline internationally and contributes important knowledge to the field likely to have a lasting influence.

[R1] Zhang, Z., Gil, A.J., **Hassan, O., & Morgan, K.** (2008). The simulation of 3D unsteady incompressible flows with moving boundaries on unstructured meshes. *Computers & Fluids*, 37 (5), 620-631. doi.org/10.1016/j.compfluid.2007.07.013

[R2] Remaki, L., Xie, Z.Q., **Hassan, O., & Morgan, K.** (2009). A high order finite volume−HLLC solver and anisotropic Delaunay mesh adaptation. *47th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition 2009*, Article number 2009-1498. doi.org/10.2514/6.2009-1498

[R3] Tremel, U., Sørensen, K.A., Hitzel, S., Rieger, H., **Hassan, O.**, & Weatherill, N.P. (2003). Parallel remeshing of unstructured volume grids for CFD applications. *International Journal for Numerical Methods in Fluids*, 53 (8), 1361-1379. doi.org/10.1002/fld.1195

[R4] Larwood, B.G., Weatherill, N.P., **Hassan, O., & Morgan, K.** (2003). Domain decomposition approach for parallel unstructured mesh generation. *International Journal for Numerical Methods in Engineering*, 58 (2), 177-188. doi.org/10.1002/nme.769

[R5] Hassan, O., Sørensen, K., **Morgan, K.**, & Weatherill, N.P. (2007). A method for time accurate turbulent compressible fluid flow simulation with moving boundary components employing local remeshing. *International Journal for Numerical Methods in Fluids*, 53 (8), 1243-1266. doi.org/10.1002/fld.1255

[R6] Evans, B., Morton, T., Sheridan, L., **Hassan, O., Morgan, K.**, Jones, J., Chapman, M., Ayers, R., & Niven, I. (2013). Design optimisation using computational fluid dynamics applied to a land-based supersonic vehicle, the BLOODHOUND SSC. *Structural and Multidisciplinary Optimization*, 47, 301-316. doi.org/10.1007/s00158-012-0826-0

Grants

[G1] Hassan, O. [Co-Investigator]. (2001-2004). Technology Development for Aeroelastic Simulation on Unstructured Grids TAURUS. [G4RD-CT-2001-00403]. FP5-GROWTH. European Commission. GBP180,000.
[G2] Hassan, O. [Principal Investigator]. (2006-2011). Platform Grant: Advances in Mesh Generation. [EP/D074258/1]. EPSRC. GBP803,405.
[G3] Hassan, O. [Principal Investigator]. (2005-2007). Collaborative Aerodynamics Simulation Toolset 2. [TP/2/ET/6/S/10264]. Technology Strategy Baord. DTI. GBP130,000.
[G4] Hassan, O. [Principal Investigator]. (2009-2016). Improving the Efficiency of Industrial Mesh Generation Capability. [45276704-616-51/14.DEC.2009]. Airbus Defence & Space. GBP80,000.
[G5] Hassan, O. [Principal Investigator]. (2011-2023). Collaborative Research Agreement with IHPC Singapore. [LT/SW/303/1011/IHPC & JF/RR/615/0116/IHPC]. IHPC. GBP50,000.
[G6] Hassan, O. [Principal Investigator]. (2007-2011). The Development of Unstructured Mesh Technology for Viscous High-Speed Flows. [EP/F032617/1]. EPSRC. GBP910,000.

4. Details of the impact

The FLITE system developed at Swansea University was adopted by Airbus, the Institute of High Performance Computing (IHPC) in Singapore and computer software developer WebSim Ltd. based in Swansea. In addition, FLITE has been used in the BLOODHOUND SSC project. Details of the impact achieved are discussed below.

Economic Impact:

At **Airbus Defence & Space** (AD&S), the unstructured meshes used in their industrial aerodynamic computations are created using the AD&S in-house mesh generator (MESHER), which is primarily based on software and mesh generation principles developed for the FLITE system by Hassan, and Morgan and acquired by AD&S in 2005. The impacts achieved are highlighted by the Group Manager and Department Director, Airbus:

"In the assessment period, the AD&S unstructured mesh generator has been applied to more than 99% of the CFD-computations conducted in the company, successfully generating hundreds of complex unstructured meshes which have formed the basis for several thousand fluid flow computations for the Eurofighter, Tornado, Eurodrone, Talarion, Next Generation Weapon System, Target Drones, as well as demonstrators and new designs. These programs in total have a volume of several hundred million euros per year. Based on its quality and run time efficiency, the mesh generator has also represented a major building block for the AD&S activities in multiple international research projects, conducted at the German, European and NATO level such as numerous Luftfahrtforschungs-Programs (LuFo), Horizon 2020 EU research programs and NATO AVT-STO projects having a total value of several tens of millions of euros. In many large national aerospace research projects, the MESHER software was a substantial pillar for the industrial research undertaken by AD&S. It is believed that the usage of numerical methods, in which the mesh generator plays a crucial role, has incurred savings in the order of several million euros and led to the development of efficient and competitive Airbus products. Based on the success of the methodology and the further enhancement provided by the Swansea team, a considerable extension of the aerodynamic simulations is planned for the near future." **[C1]**.

The Institute of High-Performance Computing is part of the Agency for Science, Technology and Research (A*STAR) in Singapore. It seeks to promote and spearhead scientific advances and technological innovations through computational modelling and simulation to tackle real-world challenges, further economic growth and improve lives. IHPC acquired FLITE in 2008 as a core capability of its multi-physics simulation framework. The system has been actively developed over

this impact period by a team of scientists in IHPC's Department of Fluid Dynamics and has been successfully employed within industrial aerodynamics, biomedical flows, precision engineering and urban environmental flow applications **[C2]**. The Group Manager and Department Director at IHPC, Singapore states:

"One of the applications with FLITE is the development of a computational fluid dynamic system for urban flow simulations targeting as an evaluation tool for the Green Mark buildings certification in Singapore (http://www.bca.gov.sg/greenmark/green_mark_buildings.html). With FLITE at the technological core, the software platform has been well tested and demonstrated for a wide range of use-cases by various users. The modelling tool is currently being adopted by industries for their building designs and energy sustainability performance evaluations." **[C2]**.

The IHPC developments based on FLITE have attracted research funding from governmental agencies and industrial partners in Singapore over the past decade and has enabled wider collaboration with other research organizations and industries **[C2]**.

WebSim Ltd, is a spinoff company that was started in 2018. The company is developing an on-demand modelling and simulation environment, based on unstructured grid technology, for a wide range of engineering applications. The environment aims at promoting modelling to SMEs and providing a platform for collaborative, multi-disciplinary design. The FLITE meshing system has been tightly integrated within the WebSim environment to provide the mesh generation capability required for any engineering modelling that requires unstructured meshes. The Director of WebSim states:

"*The integration of FLITE within WebSim environment has attracted inward investment in tens of thousands of pounds. The environment has been installed at Airbus AD&S in Germany and Spain to make use of its unique capability at providing a common working platform for collaborative design*" **[C3]**.

Impact on Practitioners and Professional Services:

The BLOODHOUND Project Team requested that the Swansea FLITE system be used to aid in the aerodynamic design process for the BLOODHOUND Super Sonic Car (SSC), a new world land speed record vehicle. Initially, FLITE was used to demonstrate the practical feasibility of designing an aerodynamic shape that was capable of safely achieving 1,000mph.

"*Without the crucial and on-going support of Swansea University, in terms of resource, expertise and the FLITE3D simulation technology, the Bloodhound project simply would not be possible. It has been the primary tool used to guide the aerodynamic design of the vehicle and led the project to a successful high speed testing campaign in Oct/Nov 2019. The subsonic and transonic aerodynamic data acquired during this testing has shown excellent agreement with the predictions made by the FLITE CFD code giving confidence in the vehicle's ability to undertake a record attempt in 2022.*

Independent analysis of the media coverage of Bloodhound Land Speed Racing's (LSR) successful high-speed test programme in the Kalahari Desert, South Africa during October and November 2019, concluded sponsors would have received a 10:1 return on their investment. A 15:1 ROI opportunity is estimated for the World Land Speed Record attempts in 2021." Bloodhound Engineering Director, Grafton LSR Ltd **[C4]**.

Impact on Understanding Learning and Participation:

A further objective of this project was to inspire a new generation of British engineers to tackle the challenges of the 21st century using science, technology, engineering, and mathematics (STEM). This resulted in the simultaneous creation of the BLOODHOUND Education Programme. This programme includes school visits for students aged seven upwards, FE roadshows and events,

the BLOODHOUND website and e-resources, the BLOODHOUND Education Centres and the BLOODHOUND Ambassadors Programme. These activities, have ensured that public engagement with the project has been a phenomenal success. The programme has increased young people's understanding of engineering and the importance of STEM subjects. Evidence of the benefit of the Bloodhound Educational Programme is highlighted in testimonials from participating schools:

"The feedback from students about their day has been really positive. The year 10's have been energised and enthused for their future choices and this has been ignited with your help. It has provided an excellent run in to year 11 where they will be studying really hard to open as many choices as possible for their post 16 education. They have now been given lots of opportunities to research, discover and aim towards….." Mrs Helen Kimber, Careers Lead, Chosen Hill School **[C5]**.

Within the reporting period over 120 ambassadors delivered more than 600 education events and activities to over 116,000 students **[C6]**. In addition, 2,500 schools have utilised the BLOODHOUND education e-resources, ensuring that the project reached over 77,000 primary and secondary school students **[C6]**.

The exposure of the education program was further enhanced following the media coverage of the successful 2019 high-speed testing in the Kalahari Desert.

"Media coverage of the high-speed test was monitored by Meltwater, an independent technology platform. They monitored global online and UK broadcast media during the two-month period and identified 2,047 unique pieces of coverage with a potential reach of five billion people. This generated a conservative Advertising Value Equivalent (AVE) figure of £46.8 million." Bloodhound Engineering Director, Grafton LSR Ltd **[C4]**.

5. Sources to corroborate the impact

Where organisations provide testimonials below, in what capacity they are involved with the impact follows in brackets:

[C1] Letter of support: Group Manager and Department Director of Airbus AD&S (Reporter)
[C2] Letter of support: Group Manager and Department of Fluid Dynamics Director, IHPC Singapore (Reporter)
[C3] Letter of support: Director of WebSim Ltd. (Reporter)
[C4] Letter of support: Director of the BLOODHOUND project, Bloodhound LSC (Reporter)
[C5] https://bloodhoundeducation.com/about-us/testimonials/
[C6] Report on Bloodhound Education Programme activities