Institution: University of Greenwich

Unit of Assessment: (UoA 11) - Computer Science and Informatics

Title of case study: Computational modelling, simulation and visualisation research supporting fire safety engineering

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

Research by the The Fire Safety Engineering Group (FSEG) has encompassed fire dynamics, fire modelling, human behaviour and evacuation modelling, and this has been applied through software engineering research and development in the creation of state-of-the-art software packages in SMARTFIRE and EXODUS. This research is saving lives worldwide because it is used to design safer aircraft, ships and buildings, and this results in social, commercial, industrial and health impacts. Economic impact stems from licensing the SMARTFIRE and EXODUS software to over 300 organisations in 32 countries and commercial applications of the software which enable the realisation of cutting-edge designs and enabling the continual safe use of heritage structures such as the Statue of Liberty. Impact on Practitioners is a result of changes to international maritime guidelines arising from FSEG research, used to inform the development of the software tools, and the wide scale use of the SMARTFIRE and EXODUS software by engineers around the world. Society impact, over and above the design of safer environments, results from FSEG research featuring in a number of popular documentary programmes attracting audiences measured in the millions.

2. Underpinning research (indicative maximum 500 words)

From it's early origins in the mid-80s, FSEG has been engaged in multi-disciplinary research, bringing together mathematicians, engineers, psychologists, computer scientists and animators to investigate fire dynamics/fire modelling and human behaviour/evacuation modelling, and develop effective software to model and better support environmental design. Initial work focused on understanding fire and human behaviour in aircraft accidents, in particular through work funded jointly by the UK CAA and EPSRC, related to the Manchester airport Boeing 737 fire. This research utilised commercial Computational Fluid Dynamics (CFD) software to develop one of the first CFD fire models to utilise body fitted co-ordinates in order to accommodate the curved configuration of the aircraft fuselage. Work in fire modelling expanded to include the simulation of fire suppression using sprinklers and water mist. However, it quickly became clear the existing commercial CFD tools lacked the power and representational capabilities to meet the needs of the researchers, and also failed to provide effective user support for fire engineers. This led FSEG to begin research, with support from the EPSRC [3a], into the development of a fire specific CFD fire simulation software tool that could be used by fire engineers, the SMARTFIRE CFD fire simulation software [3.1]. SMARTFIRE is an unstructured mesh CFD fire simulation code written in C++ which has been in a constant state of evolution, based on research developments in the underpinning models and improved software development and algorithmic approaches, since the first version in 1997. With support from industrial funding [3b, 3c] and research grants [3d-3i], FSEG has expanded the fire modelling simulation capabilities of SMARTFIRE to include advanced combustion models, toxic gas models, flame spread models and advanced smoke models [3.2-3.4]. A key feature of the development of SMARTFIRE was the use of expert systems approaches to ensure that the system was highly usable and appropriate to the needs of fire engineers, developing a novel problem set-up phase that supported non-experts, i.e. fire engineers who are not expert in CFD software modelling, to deal with the complex tasks involved in configuration of the system, such as establishing boundary conditions and meshing [3.1]. This approach not only provided benefits in computational design of the initial system, but also informs the evolution and development of the system as the FSEG team, working directly with practitioners, have generated far more effective and detailed user requirements that have informed the development of the software in terms of usability, effectiveness and general applicability. As a result, the software is now used in applications from the built environment to maritime and aviation environments.

FSEG evacuation research grew out of the fire research and was initially concerned with developing a modelling simulation and visualisation tool that could predict the behaviour of passengers subjected to a post-crash aircraft fire. This early work led to the development of the world's first microscopic evacuation model that coupled fine grained spatial resolution, human behaviour, toxicological models and fire hazard data generated from computational fire models. The research was supported through a series of research grants from the EPSRC [3d] and UK

CAA [3e] aimed at developing the prototype into a practical software tool that could couple the impact of fire to human behaviour during evacuation. The CAA funded project [3e] supported the development of the world's first practical software tool to simulate aircraft evacuation – airEXODUS [3.5]. Research continued to be funded through a series of EU funded research projects [3f, 3g] which built on the link between the CFD fire modelling capability of SMARTFIRE and the human behaviour and evacuation modelling capability of the airEXODUS software and expanded the modelling capability of both software tools, through the development of advanced combustion models to accommodate modern construction materials, and advanced behaviour models to accommodate the interaction of passengers with crew. From an early stage, FSEG research into human behaviour in evacuation scenarios included the built environment. The agent based modelling concept using a fine spatial mesh that was used to simulate aircraft evacuation was adapted to simulate evacuation of people from building environments. This required the modelling approach to be extended to represent stairs, the behaviour of people on stairs and various computational approaches to represent route finding or pathfinding, interaction with signage, group behaviour, and behaviour in smoke filled environments [3.6]. This research was funded through a variety of grants including [3b, 3c and 3h]. Leading on from this, in 1999, FSEG expanded it's research to include maritime environments. The ship environment, while similar to that of buildings, poses additional challenges. Here, the coupling of SMARTFIRE with maritimeEXODUS enabled fire to be reliably represented within a ship evacuation scenario for the first time [3i]. This work was supported by a major EU FP5 project [3i] that not only enabled data to be collected relating to the time required by passengers on ships at sea to respond to the evacuation alarm and begin the evacuation process [3.7], an essential parameter in evacuation modelling, but also data related to passenger performance in dynamic situations involving roll and the impact of smoke on passenger performance in heel and roll situations. Data generated from this work was used in the development of the maritimeEXODUS software, particularly in modelling the interaction of passenger movement in smoke filled corridors subjected to heel.

Throughout the lifetime of the evolution and development of the SMARTFIRE and EXODUS software suites, as they are now, FSEG was engaged closely with current state-of-the-art research in computer graphics, computer games, and simulation and visualisation algorithmics to achieve the best possible performance from the tools in terms of speed and accuracy of representation. In this context, it can clearly be seen that getting this research right can save lives.

3. References to the research (indicative maximum of six references)
(**Staff being submitted to UoA11 appear in bold,** other authors being submitted to other UoAs. All authors are/were members of staff within the School of Computing & Mathematical Sciences.).

3.1 S Taylor, E Galea, M Patel, M Petridis, **B Knight**, **J Ewer.** SMARTFIRE: An Integrated Computational Fluid Dynamics Code and Expert System for Fire Field Modelling. Proceedings of the 5th Int Symp IAFSS, Melbourne, Australia 1997, Ed: Y. Hasemi, pp. 1285-1296.

3.2 Z. Wang, **F. Jia**, E.R.Galea, M.K.Patel and **J. Ewer**, Predicting HCl concentrations in fire enclosures using an HCl decay model coupled to a CFD-based fire field model, Fire and Materials, 31, pp443-461, 2007, DOI: http://dx.doi.org/10.1002/fam.942.

3.3 **Jia F**, Patel M, Galea E, Grandison A, **Ewer J**, "CFD Fire Simulation of the Swissair Flight 111 In-Flight Fire – Part 2: Fire Spread analysis", The Aeronautical Journal. Vol 110, Number 1107, pp 303-314, 2006. This paper won the gold medal from the Royal Aeronautical Journal – in 2007.

3.4 Galea, E.R., **Filippidis, L.**, Wang, Z.**,** and **Ewer, J.**, "Fire and evacuation analysis in BWB aircraft configurations: computer simulations and large-scale evacuation experiment", The Aeronautical Journal, volume 114, Number 1154, pp 271-277, April 2010. This paper won the bronze medal from the Royal Aeronautical Journal in 2011.

3.5 Owen, M., Galea, E. R., Lawrence, P. J., & **Filippidis, L.** (1998). The numerical simulation of aircraft evacuation and its application to aircraft design and certification. *Aeronautical Journal*, *102*(1016), 301–312. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=2335655
This paper won the best paper award from the Royal Aeronautical Journal – The Hodgson Prize in 1999.

3.6 Xie, H.**, Filippidis, L.**, Gwynne, S., Galea, E. R., Blackshields, D., & Lawrence, P. J. (2007). Signage Distances as a Function of Observation Angle. *Journal of Fire Protection Engineering*, *17*(1), 41–64. http://dx.doi.org/10.1177/1042391507064025.

3.7 Galea, E. R., Deere, S.**,** Sharp, G., **Filippidis, L.**, Lawrence, P. J., & Gwynne, S. (2007).

Recommendations on the nature of the passenger response time distribution to be used in the MSC 1033 assembly time analysis based on data derived from sea trials. *International Journal of Maritime Engineering*, *149*(A1), 15–29. Retrieved from http://gala.gre.ac.uk/id/eprint/1076

EXAMPLE RESEARCH GRANTS:

3a. E. R. Galea. R+D of the SMARTFIRE Fire Simulation Environment. EPSRC Grant (GR/L56749/01). 1997-2000. £171k.

3b. E. R. Galea. Evacuation analysis of cable fire scenarios. Borealis project, 2001-2002. £30k.

3c. E. R. Galea. Toxicity from cable combustion in fires. Borealis, 2003-2005. £55k.

3d. E. R. Galea. *Fire and evacuation in aircraft environments.* EPSRC Grant (GR/K38250). 1996-1998. £41k.

3e. E. R. Galea. *airEXODUS development.* UK CAA Grant (7D/S/923/1and2). 1997-1999. £113k.

3f. E. R. Galea. *VELA - Very Efficient Large Aircraft.* EU FP5 (G4RD-CT2002-00842). 2002-2004. £130k (UoG component).

3g. E. R. Galea. *NACRE* (Project concerned with fire+evacuation analysis of Blended Wing Body aircraft). EU FP6 (project 516068). Apr 2005 – Mar 2009. €590,000.

3h. E. R. Galea. *HEED Consortium (led by FSEG and Professor Galea involving Universities of Ulster and Liverpool. Project concerned the evacuation of the World Trade Centre).* EPSRC (GR/S74201/01 and EP/D507790). Sept 2004 – Oct 2007. £1.5 million.

3i. E. R. Galea. EU FP5 Fire Exit (contract GRD2-2001-50055). 2001-2005. £325k.

The quality of this research is demonstrated through the award of national and international prizes:

- 2011, Royal Aeronautical Society's Bronze Award for a paper published in 2010, "Fire and Evacuation analysis in BWB aircraft configurations: computer simulations and large-scale evacuation experiment", which appeared in the Aeronautical Journal,
- 2007, Royal Aeronautical Society's Gold Award and George Taylor Prize for the best paper published in 2006, "CFD Fire Simulation of the Swissair Flight 111 In-Flight Fire – Part 2: Fire Spread analysis", which appeared in the Aeronautical Journal.
- 2003/2004 European IST prize by the European Council of Applied Sciences, Technology and Engineering (Euro-CASE) for the development of the EXODUS suite of software.
- 2003 Royal Aeronautical Society Hodgson Prize for best paper on a safety topic for a publication Prof Galea co-authored, entitled, "Examining the effect of exit separation on aircraft evacuation performance during 90 sec certification trials", which appeared in the Aeronautical Journal 2002.
- The 2001 RINA/LR Safer Ships Award (Royal Institution of Naval Architects/Lloyds Register).
- • The 2001 British Computer Society award for IT 2001 for the development of EXODUS, citation:

"The winners not only demonstrate technical innovation, but also show how technology can be used to benefit society at large." Judith Scott, Chief Executive of The BCS.

4. Details of the impact (indicative maximum 750 words)

1) Economic Impact: During the assessment period, Greenwich University Enterprises Limited (GUEL), the commercial arm of the University of Greenwich, has generated over £837k from licensing the EXODUS software to 250 licensees in 32 countries and £230k licensing the SMARTFIRE software to 64 organisations in 16 countries. These licensees, ranging from engineering consultancies, regulatory authorities and national laboratories, use the software to explore the evacuation safety of complex structures, ensuring that they are safe and fit for purpose thereby generating considerable consultancy income. Example projects that have used the EXODUS software include the Airbus A330-X, A340 and the initial design of the Airbus A380 [5.1]. FSEG and the airEXODUS software were used in the preliminary design of the multi-billion euro A380 where it was used to assist AIRBUS in selecting a configuration for the largest passenger aircraft in the world that would meet international regulatory requirements for evacuation. Towards the end of the design programme, Airbus again used FSEG and airEXODUS to de-risk the A380 full-scale evacuation certification trial, saving the manufacturer potentially millions of euro by identifying possible problems that may occur during the certification trial and ensuring that the A380 was a safe aircraft [5.1]. The A380 comfortably passed the evacuation certification trial and is an aviation success story flying with the worlds leading airlines. airEXODUS has also been used by the Canadian aircraft manufacturer BOMBARDIER to assess the evacuation capabilities of a number of their aircraft while still in the early design stages including the Dash8-400, C-Series regional jet and the T507 project, ensuring that the proposed configurations will meet international evacuation certification requirements [5.2]. Thus airEXODUS is used to save aircraft manufacturers tens of millions of dollars/euros in wasted development costs and lost sales

revenues by ensuring that the aircraft will pass the certification trial and thereby also ensures that the design is safe for the travelling public [5.1, 5.2].

A unique version of buildingEXODUS is being incorporated within the security system of the Pentagon as part of project Pentagon Shield. This makes use of special software features e.g. parallel computing implementation, CBRN toxicity model capability (based on the SMARTFIRE developments) to enable faster than real time determination of optimal evacuation routes for building occupants during an incident. Battelle/DoD/Hughes turned to FSEG and buildingEXODUS when US based evacuation software was found to be inadequate, potentially jeopardising a multi-million dollar project [5.3]. Up until quite recently, the SMARTFIRE-EXODUS coupling was the only modelling environment that could bring together the detailed interaction of people and fire. The EXODUS and SMARTFIRE software tools provide fire engineering firms a competitive edge when bidding for projects, allowing them to win important contracts, generating significant income for the companies. An example is the use of buildingEXODUS, under license, by Hughes Associates to undertake an assessment of the life safety and emergency management systems within the Statue of Liberty [5.3]. Following this assessment and remodelling work, the Statue of Liberty was reopened to the public by President Obama in 2009. Another example is the use of SMARTFIRE by Fire Engineering firm FDS on the Greenwich Reach project where it assisted FDS in delivering a project worth over £1 million to FDS [5.4].

2) Impacts on Practitioners and Professional Services: Work carried out by FSEG in collecting empirical data to ensure accuracy of the models of human behaviour utilised in the maritimeEXODUS software [3.7] also demonstrated that the data used in the International Guidelines on Ship Evacuation Analysis was incorrect and could lead to an incorrect assessment of the suitability of a ship design for evacuation. This led to changes to the IMO evacuation guidelines and hence to international practice in ship design [5.5, 5.6]. As already stated under Economic impact, over the assessment period, the EXODUS and SMARTFIRE software has been used by over 300 licensees in 32 countries and so has become a standard engineering design tool for safety analysis, used by fire safety engineers around the world. The software is therefore having an impact on the engineering profession around the world [5.3, 5.4].

3) Impacts on Society, Culture and Creativity: FSEG research into fire and evacuation has engaged the public, informing them of our research, educating them concerning risks associated with fire and evacuation and how they can minimise those risks, as well as informing future industrial partners and policy makers. This has been achieved through several high profile TV and Radio programmes which have featured our research such as the BBC 'Horizon' documentary based on FSEG fire and evacuation research, entitled, "How to Survive a Disaster" (first broadcast 10/03/09 on BBC1 [5.7] which attracted a 1.7 million viewer audience representing 7% of the audience that night [5.8]). The concepts presented in this programme were considered so important; the US news programme ABC Nightline featured a story on its nightly news programme broadcast on 22/12/09 which drew on much of the material presented in the Horizon programme [5.9]. Other programs include the Channel 4 documentary "Terror at Sea" (first broadcast 31/01/12 on Channel 4, [5.10]) which followed the sinking of the Costa Concordia. Prof Galea commented on evacuation issues associated with large cruise ships (the programme attracted a massive 3.4 million viewers (http://bit.ly/17BJjP1) which was followed up by an interview on BBC Radio 4 Today (4 March 2012, (http://bit.ly/GAKPrP).

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Airbus Chief Engineer, France.
5.2 Bombardier Senior Designer, Concept Design Team, Canada.
5.3 Hughes Associates, Principal, USA..
5.4 FDS Managing Director, UK.
5.5 International Guideline Document, IMO MSC Circ 1238 - http://bit.ly/15W1tI9, Annex2, p6
5.6 Director Centre for International Cooperation, National Maritime Research Institute, Japan.
5.7 http://bbc.in/15noerY; 5.8 http://bit.ly/17BHAJx; 5.9 http://bit.ly/1h8jGwP
5.10 http://bit.ly/17BIXHU