Institution: University of Greenwich

Unit of Assessment: 11 - Computer Science and Informatics

Title of case study: Enhancing the safety of aircraft, ships and built environment around the world through the transformative application of computer modelling in fire safety engineering

Period when the underpinning research was undertaken: January 2000 - December 2020

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:
Prof Ed Galea	Professor	01/02/1986 – present
Dr John Ewer	Research Fellow	02/03/1992 – present
Dr Angus Grandison	Research Fellow	04/10/1993 – present
Dr Fuchen Jia	Research Fellow	01/12/1997 – present
Dr Zhaozhi Wang	Research Fellow	01/12/1998 – present
Prof Mayur Patel	Professor	01/05/1987 – present
Dr Peter Lawrence	Reader	07/02/1994 – present
Dr Steven Deere	Research Fellow	01/04/2009 – present
Dr Hui Xie	Research Fellow	01/04/2003 – present
Mr Lazaros Filippidis	Research Fellow	02/01/1996 – present
Mr Darren Blackshields	Research Fellow	01/09/1999 – present

Period when the claimed impact occurred: August 2013 - July 2020

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

1. Summary of the impact

The Fire Safety Research Group's (FSEG) research in fire dynamics, human behaviour, and fire and evacuation modelling has driven the development of state-of-the-art software tools, SMARTFIRE and EXODUS. The societal impact of this research is evidenced by its contribution to the design of safer aircraft, ships and buildings globally. FSEG has generated economic impact from over 300 software license sales to organisations in over 30 countries, which have applied the software commercially to build safety into innovative designs. The research has led to, or enabled, the development of innovative safety products, such as dynamic and adaptive emergency signage, and low-cost domestic fire suppression systems. Public policy impacts entail the UK government's use of its research to frame guidelines on the positioning of security bollards, and the Grenfell Inquiry's adoption of FSEG recommendations to improve the safety of residential high-rise buildings. Impact on practitioners is demonstrated by their use of the government guidelines on security bollards, the application of EXODUS by UK government security services to assist in mitigating terrorist threats, and the wide-scale use of the FSEG software by engineers globally.

2. Underpinning research

From its inception, FSEG has engaged in multi-disciplinary research, bringing together computer scientists, mathematicians, engineers, psychologists and 3D modellers to investigate fire dynamics and human behaviour, develop effective software to model fire and evacuation, and support the design of safer environments. Initial research focused on understanding fire and human behaviour in aircraft accidents, through projects funded jointly by the UK CAA and EPSRC. This utilised commercial Computational Fluid Dynamics (CFD) software to develop one of the first CFD models to simulate fire within the complex environment of an aircraft cabin. Limitations of commercial CFD software to represent complex geometries and provide effective user support for fire engineers led FSEG, with EPSRC support **[3a]**, to research and develop a more sophisticated fire specific CFD simulation software tool that could be used easily by fire engineers: SMARTFIRE **[3.1,** 2001**]**. SMARTFIRE is an unstructured mesh CFD fire simulation code written in C++. Research into its core physics sub-models, numerical solution algorithms and visualisation techniques, has driven its constant development.

Industrial funding **[3b-3d]** and research grants **[3e-3g]**, supported FSEG to expand the fire simulation capabilities of SMARTFIRE to include water mist suppression **[3d]**, advanced combustion, toxic gas, flame spread, advanced smoke models, as well as parallel computing techniques utilising networked PCs with dynamic load balancing to improve performance **[3.1-3.6,** 2001-2020**]**. A key feature of SMARTFIRE was the use of a knowledge-based systems approach to make the system highly usable by, and appropriate to, the needs of fire engineers, including a novel problem set-up phase supporting those not expert in CFD modelling. Close collaboration

with practitioners informed development of the software's capabilities and utility, including assisting users to handle complex setup tasks, such as boundary condition specification and meshing **[3.3-3.5,** 2006-2020**]**. This responsiveness assisted SMARTFIRE's development, and its adoption for applications throughout the built **[3.2,** 2007**]**, maritime **[3.5,** 2020**]** and aviation environments **[3.3,** 2006**, 3.4,** 2017**]** worldwide. Applications include embedded advanced fire simulation within immersive training environments **[3.5, 3c, 3g]**.
To understand how fire impacts safety, it is essential to consider both fire and human dynamics, and how they interact. Modelling both fire development, and human behaviour and evacuation, is therefore vital. FSEG software achieves this by coupling fire and evacuation simulations of populations exposed, and reacting, to the developing fire. The group's evacuation research focused initially on developing a simulation tool that could predict the behaviour of passengers evacuating from a post-crash aircraft fire. This led to the development of the world's first agent-based evacuation model coupling fine-grained spatial resolution, adaptive human behaviour, toxicological models and fire hazard data: airEXODUS **[3.4]**. A series of EU-funded aviation fire safety research projects, e.g. **[3e]**, built on the unique interactive coupling between fire simulation (SMARTFIRE), human behaviour and evacuation modelling (airEXODUS). The sophistication of both the fire and evacuation modelling tools was enhanced over the years through development of advanced combustion models to accommodate modern materials, including composites, and advanced rule-based behaviour models to simulate the interaction of passengers with cabin crew. These advanced modelling capabilities enabled the coupled airEXODUS – SMARTFIRE software to address complex fire scenarios involving interaction of people with the evolving fire environment e.g., explaining why 55 people lost their lives in the Manchester Boeing 737 fire from 1985 **[3.4]**.

FSEG evacuation research expanded to include the built environment. The agent-based modelling concept using a fine spatial mesh was adapted from aircraft evacuation. A variety of grants including **[3h, 3i]**, supported the extension of the modelling to represent behaviour associated with stairs, route-finding, movement of the mobility impaired, interaction with signage, groups, movement in smoke filled environments, elevators etc **[3.7,** 2001**, 3.8,** 2016**]**. These behavioural and modelling capabilities were further enhanced to include the ability to simulate the impact of marauding armed terrorists in crowded places **[3.9,** 2018**]**. To address real-time applications, FSEG developed the world's first parallel implementation of a rule-based evacuation model. The approach, using domain decomposition and dynamic load balancing, also enables the simulation of extremely large problem domains **[3.10,** 2017**]**.
The value of FSEG research on behaviour in the built environment extends beyond evacuation models. Research into how people react to signage revealed that only 38% 'see' conventional static emergency signage in emergency situations **[3.8]**. To address this and enable signs to adapt to the evolving hazard environment, FSEG developed the concept of the Active Dynamic Signage System (ADSS). This was developed and demonstrated further in the EU FP7 GETAWAY project, improving detection of signs by over 100% **[3i, 3.8]**. The concept's value was recognised in 2014 through 'The Guardian University Award for Research Impact' (http://bit.ly/FSEG_guardian_award). Another example is FSEG research characterising the interaction of pedestrians with security bollards, which demonstrated that strategically placed bollards had little negative impact on exit flow **[3k, 3.11,** 2014**]**.

FSEG research again expanded to include maritime/ship environments, which pose additional challenges, such as a heeled deck, and the impact of lifejackets, on human performance. Here, the coupling of SMARTFIRE with maritimeEXODUS enabled fire to be reliably represented within a ship evacuation scenario for the first time **[3j]**. This work was supported by a major EU FP5 project **[3j]** enabling the collection of data on the time required by passengers on ships at sea to respond to the evacuation alarm and begin the evacuation process **[3.12,** 2007**]**, an essential parameter in evacuation modelling. It also enabled data collection on passenger performance in dynamic situations involving roll, and the impact of smoke on passengers in heel and roll situations. Data generated from this work was used in the development of the maritimeEXODUS software **[3.5, 3.12]**, particularly in modelling the interaction of passenger movement in smoke-filled corridors subjected to heel. The significance of this was recognised through the 2001 Royal Institution of Naval Architects/Lloyds Register 'Safer Ships' award.

The overall quality of FSEG research is demonstrated through the award of several national and international prizes: • **2001 British Computer Society award for IT**, CEO Judith Scott commenting, *"The winners not only demonstrate technical innovation, but also show how technology can be used to benefit society at large.";* • **2002 Queen's Anniversary Prize:** *"The University is a recognised world leader in the area of evacuation model development. Use of its software technology by businesses and public authorities greatly enhances public safety and its specialised training offers vital expertise to the user community worldwide."*

3. References to the research

1. **Wang, Z., Jia, F., Galea, E.R., Patel, M.K., Ewer, J**. "Simulating one of the CIB W14 round robin test cases using the SMARTFIRE fire field model." Fire Safety Journal, 36, pp661-677, 2001. https://doi.org/10.1016/S0379-7112(01)00018-2
2. **Galea E.R., Jia F.,** and **Wang Z**. "Predicting toxic gas concentrations resulting from enclosure fires using local equivalence ratio concept linked to fire field models". Fire and Materials, Vol 31, Issue 1 pp 27-51, Jan/Feb 2007. https://doi.org/10.1002/fam.924
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. https://doi.org/10.1017/S0001924000013178. *This paper won the 2017 gold medal from the Royal Aeronautical Journal.*
4. **Galea, E.R., Wang, Z.,** and **Jia, F** (2017). Numerical Investigation of the Fatal 1985 Manchester Airport B737 Fire, The Aeronautical Journal, Vol 121, Number 1237, pp. 287-319. https://doi.org/10.1017/aer.2016.122. *Winner 2017 gold medal from Royal Aeronautical Journal*
5. Woolley, A**., Ewer, J., Lawrence, P., Deere, S.,** Travers, A., Whitehouse, T., **Galea, E.R.** A naval damage incident recoverability toolset: Assessing naval platform recoverability after a fire event, Ocean Engineering, (2020), 207, 107351. https://doi.org/10.1016/j.oceaneng.2020.107351
6. **Grandison, A. Galea, E.R., Patel, M.K.,** and **Ewer.J**. Parallel CFD fire modelling on office PCs with dynamic load balancing, Int J Numer Meth Fluids, 55, pp29-39, 2007. https://doi.org/10.1002/fld.1278
7. Gwynne S., **Galea, E. R., Lawrence, P.J.** and **Filippidis, L.** "Modelling Occupant Interaction with Fire Conditions Using the buildingEXODUS model". Fire Safety Journal, 36, pp327-357, 2001. https://doi.org/10.1016/S0379-7112(00)00060-6
8. **Galea, E. R., Xie, H., Deere, S.,** Cooney, D., and **Filippidis, L**. (2016) An international survey and full-scale evacuation trial demonstrating the effectiveness of the active dynamic signage system concept. Fire and Materials. https://doi.org/10.1002/fam.2414
9. **Galea E.R., Blackshields, D., Lawrence. P., Deere, S**. Simulating a Marauding Terrorist Firearms Attack (MTFA) ** * **, Final Report. 23/02/18. Secret Report for DSTL and DfT.
10. **Grandison, A.,** Cavanagh, Y., **Lawrence, P.J. and Galea, E.R.** (2017). Increasing the simulation performance of large-scale evacuations using parallel computing techniques based on domain decomposition, Fire Technology, 53, pp1399-1438. https://bit.ly/38gQ8Md
11. **Galea, E.R.,** Cooney, D., **Xie, H.,** Sharp, G.G. Impact of Hostile Vehicle Mitigation Measures (Bollards) on Pedestrian Crowd Movement. Phase 2 Final Report, Dept for Transport, CPNI, Oct 2014. Published on UK government website on 15 Nov 2016. https://bit.ly/3bit3uq
12. **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. http://gala.gre.ac.uk/id/eprint/1076

Example research grants:

a. **E. R. Galea**. EPSRC Grant (GR/L56749/01). The SMARTFIRE Fire Simulation Environment. 1997-2000. £171,000.
b. **E. R. Galea**. Borealis projects, Evacuation (Pt1) and Fire toxicity (Pt2), Jan 02 – Mar 05, £85,000.
c. **E. R. Galea**. Australian DSTO. Virtual ship simulator. Part I – III, Jan 14 – Feb 18, £202,000
d. **E. R. Galea.** TSB/EPSRC (SKTP). Plumis (project 1000921), Water Mist Fire Suppression Modelling, Nov 13 – Nov 14, £48,550.
e. **E. R. Galea**. EU FP6 (project 516068): NACRE, Apr 05 – Mar 09. €590,000.
f. **E. R. Galea**. EU FP7 (project 218761): FIREPROOF. Jun 09 – Jun 12, €345,000

- **g. E. R. Galea**. EU Horizon2020 (project 653590): AUGGMED, Jun 15 – May 18, €640,000
- **h. E. R. Galea**. Part of HEED Consortium (Project concerned the evacuation of the World Trade Centre). EPSRC (GR/S74201/01 and EP/D507790). Sep 04 – Oct 07. £1.5 million.
- **i. E. R. Galea**. EU FP7 (project no. 265717): GETAWAY. Nov 11 – Oct 14, €572,438
- **j. E. R. Galea**. EU FP5 (contract GRD2-2001-50055): Fire Exit. 2001-2005. £325,000.
- **k. E. R. Galea**. CPNI (UK Home Office). Experimental analysis of the impact of Bollard Arrays on Pedestrian movement – Parts I and II, Nov 12 – Aug 15, £200,000.

4. Details of the impact

(1) Economic Impact: (i) During the REF period, UoG has generated over £1.15million from over 300 license sales of SMARTFIRE and EXODUS software to organisations in over 30 countries **[5.1]**. **(ii)** Licensees included engineering consultancies e.g. Bureau Veritas, regulatory authorities e.g. China Maritime Classification Society, national laboratories e.g. DSTO Australia. The software was used in cutting-edge design to explore and improve the evacuation safety of complex structures, generating considerable consultancy income. EXODUS software was used for the Airbus A330-X, A340 and A380 projects **[5.2]**. FSEG and the airEXODUS software were used in the preliminary design of the multi-billion-euro A380, and to de-risk the A380 full-scale evacuation certification trial. The software, and the research underpinning it, contributed to the A380's safety **[5.2]** and potentially saved the manufacturer millions of euros by identifying possible problems that might occur during the trial, which could have caused cost overruns, resulting in a higher unit cost. Through the REF period, the A380 world fleet safely carried 150 million passengers over 3.3 million flight hours. Since 2013, Airbus has delivered 131 A380s, with 228 in service (May 2020). FSEG research assisted these sales by contributing to product safety, and keeping the price down, critical considerations for airline customers **[5.2]**. **(iii)** FSEG fire modelling expertise and SMARTFIRE fire simulation software assisted three-person start-up company PLUMIS to develop and refine their innovative prototype fire suppression system into an efficient cost-effective life-saving product. In just 12 years, the start-up has grown to have a £3.2M turnover employing 43 people **[5.3]**. **(iv)** EXODUS and SMARTFIRE tools give fire engineering firms a competitive edge when bidding for projects, enabling them to win important contracts, generating significant income. Examples during the REF period include global engineering firms Arcadis and Thornton Tomasetti which used FSEG software, under license, to undertake early design assessments of the life safety and emergency management systems for major projects such as Rolls Royce Goodwood (UK), Jaguar Land-Rover Castle Bromwich (UK) **[5.4]**, a large Data Center in the USA and a car rental facility at a major US airport **[5.5]**. **(v)** FSEG research, which lead to the development of the ADSS concept **[3i]** has created a new market in emergency signage technology. The ADSS concept improves signage detectability 100% enabling the sign to adapt to a changing hazard environment **[3.9]**. Signage manufacturers globally have adopted and adapted the concept. EVACLITE and CLEVERTRONICS are 2 companies focused on the FSEG ADSS concept. EVACLITE was set up in the UK to manufacture and sell ADSS **[5.6]**. CLEVERTRONICS, Australia's leading emergency lighting company, adopted the ADSS concept and started a new business to develop and manufacture the product **[5.7]**. They are both founded on the FSEG concept, with many other companies globally adapting similar concepts based on FSEG fundamental research.

(2) Impact on Public Policy. (i) Security bollards have become a common feature protecting public spaces, part of the UK's Hostile Vehicle Mitigation strategy. The Centre for the Protection of National Infrastructure (CPNI) is the government organisation reporting to the Home Office that advises on security issues related to national infrastructure. CPNI had produced guidance on the positioning of bollard arrays, but the advice did not include their impact on evacuation flow. This is an important issue because the initial evacuation safety analysis used in the design and certification of these structures did not take into consideration that a ring of security bollards would be placed outside the exits. FSEG research, sponsored by CPNI and DfT **[3k]**, investigated the impact that security bollards have on evacuation flows using a series of full-scale experiments, which identified and quantified, for the first time, not only how bollards impact evacuation flow, but also how they could be positioned to minimise their impact **[3.11]**. The research resulted in a new set of DfT guidelines (written by **Prof Galea**), which are used internationally to optimally position security bollards around critical infrastructure **[5.8]**. **(ii) Prof Galea**, one of six experts to the Grenfell Fire Inquiry, provided a report to the Inquiry containing 42 evidence-based **[3.7]** interim recommendations to improve evacuation of residential high-rise buildings **[5.10]**. Of these, 22 were partially/fully adopted in the Chairman's Phase 1 report. For example, recommendation 2.9 on luminous floor numbering was adopted as recommendation 15 (para 33.27); recommendation 2.11 on PEEPs was adopted as recommendation 12e (para 33.22), and recommendations 3.1–3.3 and 3.6-3.8 on full building evacuation were adopted as recommendation 12a (para 33.22) **[5.11]**. The recommendations aim to improve public safety through UK regulatory/policy change.

(3) Impacts on Practitioners and Professional Services. (i) The new guidelines **[5.8]** for optimal positioning of bollard arrays impact professional practice through the modification of the previous design practice. **(ii)** A restricted version of the EXODUS software has been developed for use by UK government security services to assist in planning mitigation strategies for marauding armed terrorists in crowded places **[3.9]**. The use of this approach has had a significant impact on how security professionals plan for and develop counter measures **[5.9]**. **(iii)** Over the REF period, FSEG software has been used by over 300 licensees in 30 countries (see 1i), becoming standard engineering design tools for safety analysis, used by fire safety engineers around the world. The software therefore has impact on engineering professional practice globally **[5.4, 5.5]**.

(4) Impacts on Social Welfare. (i) The main impact of FSEG research on society is public safety: safer aircraft, buildings and passenger ships through more effective safety standards and policy, and safer designs. Examples: ensuring that security bollards around infrastructure have minimum impact during emergency evacuation (see 2i); through the introduction of novel concepts in emergency signage, making them more effective, and buildings safer (see 1v); through recommendations to improve safety of residential high-rise buildings (see 2ii); through assisting in the development of cost-effective water mist fire suppression systems for domestic environments, now installed in over 5000 UK properties (incl. 350 sheltered scheme flats), to protect the most vulnerable from fire (see 1iii). **(ii)** Members of the public make an important contribution to their personal safety, safety of families and of society. Engagement to improve public understanding of safety and how to minimise risks associated with fire and evacuation is therefore critical, and a further societal impact of FSEG. FSEG promotes public understanding of science via the media, helping to build resilience to science scepticism, which the COVID-19 pandemic has highlighted as a growing issue. This is achieved through media coverage of FSEG research and interviews with **Prof Galea** on evacuation and pedestrian dynamics. It has also informed future industrial partners and policy makers. Examples: FSEG research on pedestrian interaction with autonomous vehicles: BBC Radio 4 'All in the Mind', 08/05/18 (https://bbc.in/2yBjxxZ). Importance of standing on London Underground escalators in rush hour: BBC Radio 4 Today, 10/03/16 (audience 1.2m); BBC Radio 5 Breakfast Programme, 07:25, 18/01/16 (audience 444k); BBC World Service Weekend Programme 07:50 16/04/16. FSEG EU Horizon2020 project AUGGMED, developing VR training environments for security services: BBC CLICK 28/04/17 (https://bbc.in/3qdBuLW). **Prof Galea** interviews on Grenfell Tower Fire: BBC Radio 4 Inside Science 15/06/17 (https://bbc.in/3uVOmdg);NYTimes, (4.7m digital subscription) 24/06/17 (https://nyti.ms/3qiPeFh), The Economist, (24/07/17) (1.7m global print and digital circulation), (https://econ.st/2yFZXR9).

5. Sources to corroborate the impact

1. University of Greenwich sales accounts, SMARTFIRE & EXODUS licences (Aug 13–July 20)
2. Testimonial: Airbus Chief Engineer, France.
3. Testimonial: Plumis Director, UK
4. Testimonial: Arcadis, Associate Technical Director, UK
5. Testimonial: Thornton Tomasetti, Principal, UK
6. Evaclite: identifies FSEG research incl GETAWAY [3i] https://www.evaclite.com/about-us/; https://www.evaclite.com/directional-safety-signage-systems/
7. Testimonial: Clevertronics Managing Director, Australia
8. Traffic Advisory Leaflet 01/16, 15 Nov 2016, Dept for Transport. http://bit.ly/UKgov-bollards
9. Testimonial: DSTL, lead Modelling and Simulation Strategy, Platform Systems Division, UK
10. Galea E.R., Interim Phase 1 Recommendations for the Grenfell Inquiry - Final, 02/04/19. https://bit.ly/3qkzbXm
11. Grenfell Tower Inquiry: Phase 1 Report. Chairman: The Rt Hon Sir Martin Moore-Bick October 2019. Vol 4 (Part 5). https://bit.ly/3kNvQPr