Institution: University of Greenwich

Unit of Assessment: 12 - Engineering

Title of case study: Fire Safety Engineering Group (FSEG) evacuation research: ensuring the safety of people using aircraft, ships and the built environment around the world

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 Peter Lawrence	Reader	07/02/1994 – present
Dr Steve Deere	Research Fellow	01/04/2009 – present
Dr Hui Xie	Research Fellow	01/04/2003 – present
Dr Lynn Hulse	Research Fellow	01/11/2005 – 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 societal impact of FSEG's research on human behaviour is evidenced by its contribution to the design of safer aircraft, ships and buildings around the world. FSEG has generated economic impact from over 200 license sales of EXODUS software to organisations in over 30 countries, which have applied the software commercially to build safety into cutting-edge designs. FSEG's research has led to the creation of an entirely new market for emergency signage, through the development of a new type of dynamic and adaptive emergency exit sign. Public policy impact is evidenced by Australian government aviation safety policy, International Maritime Organisation evacuation guidelines for large passenger ships, and new UK government security guidelines for positioning security bollards, all of which were influenced directly by FSEG's aviation, maritime or pedestrian research. Impact of FSEG research on practitioners is evidenced by the effect of these policies on daily practice internationally, and the use of EXODUS software by UK government security services to assist in mitigating terrorist threats, and by engineers throughout the world.

2. Underpinning research

Early evacuation modelling research at the University of Greenwich focused on understanding human behaviour in aircraft evacuation. This led to the development of a prototype of the airEXODUS software. Analysis of accounts from survivors of aircraft accidents further improved understanding of human behaviour in aviation accidents, resulting in the development of a relational database of these experiences – the AASK database **[3.1**, 2005**]**. The research established that representing complex human behaviour was essential if evacuation models were to predict evacuation dynamics accurately. It led to the development of the world's first agent-based evacuation model, coupling fine-grained spatial resolution, human behaviour, toxicological models and fire hazard data – airEXODUS **[3.2**, 2002**]**. Research continued through EU and aircraft industry-funded research projects **[3a, 3b]**.

FSEG evacuation research expanded to the built environment. Human behaviour research identified and quantified typical behaviour and performance in emergency situations associated with buildings, e.g., domestic fires **[3c]** and high-rise buildings **[3d, 3.3**, 2010**]**. It included the impact of culture **[3e]**, signage **[3f, 3.4**, 2012**]**, assist devices for the mobility-impaired **[3.5**, 2015**]**, elevators and security bollards **[3g, 3.6**, 2014**]**. This research underpinned the development of an agent-based model to simulate evacuation from the built environment: buildingEXODUS. Agent-based modelling was extended to represent behaviour associated with stairs, and various mathematical approaches were applied to represent route-finding, interaction with signage, group behaviour, 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 **[3h, 3.9**, 2018**]**.

The value of FSEG research on behaviour in the built environment extends beyond the development of evacuation models. For example, research into how people react to signage revealed that only 38% 'see' conventional static emergency signage in emergency situations **[3.4]**.

To address this issue and enable signs to adapt to the evolving hazard environment, FSEG developed the concept of the Active Dynamic Signage System (ADSS). It was developed and demonstrated further in the EU FP7 GETAWAY project, improving detection of signs by over 100% **[3f, 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 **[3g, 3.6]**.

FSEG research expanded to include maritime/ship environments, which pose additional challenges to model development, such as the impact on human performance of a heeled deck, and the use of lifejackets, much of which was unknown or unquantified. The collection of human performance data on inclined decks (i.e., static heel/trim) was enabled by the construction of a large-scale simulator (SHEBA) in Canada **[3.10**, 2002**]**. Further research measured the time required by passengers on ships at sea to respond to the alarm and begin the evacuation process **[3.11**, 2013**]**, an essential parameter in evacuation modelling. The maritime research, which was funded through a variety of grants **[3i]**, generated data for the development of maritimeEXODUS **[3.10]**. The significance of the FSEG research was recognised through the award of the 2001 Royal Institution of Naval Architects/Lloyds Register 'Safer Ships' award.

FSEG research has been awarded several other 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.";* • **2019 Society of Fire Protection Engineers (UK Chapter) Best Research Project of the Year:** *"Outstanding, unique and informative research in an area seldom explored. There is great potential to make the construction environment and all those who work in it safer from fire and this research provides data and tools to achieve this objective."*

3. References to the research

1. **Galea, E. R.,** Finney, K. M., Dixon, A., Siddiqui, A., & Cooney, D.P. (2005). An analysis of the passenger to cabin crew ratio and exit reliability based on past survivable aviation accidents. *Human Factors and Aerospace Safety, 5*(3), 239–256. http://trid.trb.org/view.aspx?id=786307
2. Blake, S. J., **Galea, E. R.,** Gwynne, S., **Lawrence, P. J.,** and **Filippidis, L**. "Examining The Effect Of Exit Separation On Aircraft Evacuation Performance During 90-Second Certification Trials Using Evacuation Modelling Techniques". The Aeronautical Journal, 106,1055, pp1-16, January 2002. https://doi.org/10.1017/S0001924000018054 *This paper won the best paper award from the Royal Aeronautical Journal – The Hodgson Prize in 2002.* Also available: https://gala.gre.ac.uk/id/eprint/507/
3. McConnell, N.C., Boyce, K.E. Shields, J., **Galea, E.R.,** Day, R.C. and **Hulse. L.M.** "The UK 9/11 evacuation study: Analysis of survivors' recognition and response phase in WTC1". Fire Safety Journal 45, pp 21–34, 2010. http://dx.doi.org/10.1016/j.firesaf.2009.09.001.
4. **Xie, H., Filippidis, L., Galea, E.R., Blackshields, D.,** and **Lawrence P**. "Experimental Analysis of the Effectiveness of Emergency Signage and its Implementation in Evacuation Simulation", Fire and Materials, Vol 36, pp 367-382, 2012. http://dx.doi.org/10.1002/fam.1095
5. Hunt, A., **Galea, E.R., Lawrence, P.J.** An analysis and numerical simulation of the performance of trained hospital staff using movement assist devices to evacuate people with reduced mobility, Fire and Materials, Vol 39, Issue 4, pp 407-429, 2015. http://dx.doi.org/10.1002/fam.2215
6. **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
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, Vol 41, Issue 5, pp 493-513. http://onlinelibrary.wiley.com/doi/10.1002/fam.2414/full ***[REF2 Submission - Identifier 15912]***
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. **Galea, E. R., Filippidis, L.,** Gwynne, S., **Lawrence, P. J.**, Sharp, G., & **Blackshields, D**. (2002). The Development of an Advanced Ship Evacuation Simulation Software Product and Associated Large Scale Testing Facility for the Collection of Human Shipboard Behaviour Data (pp. 37–50). Proceedings of the International Conference on Human Factors in Ship Design and Operation, The Royal Institution of Naval Architects, London. Retrieved from http://www.opengrey.eu/item/display/10068/668128
11. Brown, R., **Galea, E.R., Deere, S.,** and **Filippidis, L**. "Passenger Response Time Data-Sets for Large Passenger Ferries and Cruise Ships Derived from Sea Trials", The Transactions of the Royal Institution of Naval Architects, International Journal of Maritime Engineering, ISSN 1470-8751, Vol 155, Part A1, pp33-47, 2013. http://www.rina.org.uk/ijme_251.html *This won best paper award from Royal Institution of Naval Architects – The Medal of Distinction 2013.*

Example research grants:

a. **E. R. Galea**. *NACRE* (Project concerned with fire+evacuation analysis of Blended Wing Body aircraft). EU FP6 (516068). April 2005–March 2009. €590,000;
b. **E. R. Galea**. AIRBUS (France/Germany) funded analysis of A380 evacuation capabilities. December 2005–March 2006. £31,000.
c. **E. R. Galea**. TSB/EPSRC (KTP009153). Kent Fire and Rescue Service, LIFEBID, understanding behaviour in domestic fires, July 2013–August 2016, £158,250.
d. **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, EP/D507790). September 2004–October 2007. £1.5 million.
e. **E. R. Galea**. EU FP7 (No. 218324): BeSeCu. (May 2008–December 2011), €600,000
f. **E. R. Galea**. EU FP7 (No. 265717): GETAWAY. November 2011–October 2014, €572,438
g. **E. R. Galea**. CPNI (UK Home Office). Experimental analysis of the impact of Bollard Arrays on Pedestrian movement – Parts I and II, November 2012–August 2015, £200,000.
h. **E.R.Galea**. DSTL/DfT. Modelling train security threats (September 2017–January 2018, January 2020–August 2020), £200,000.
i. **E. R. Galea**. *Ship Evacuation.* EPSRC (GR/T22100/1). 2004–2007. £256,000.

4. Details of the impact

(1) Economic Impact. (i) During this REF period, UoG generated over £879,000 from over 200 license sales of EXODUS software to organisations in over 30 countries **[5.1]**. **(ii)** Licensees included engineering consultancies e.g., Babcock, regulatory authorities e.g., the US Dept of Transportation, and national laboratories e.g., the National Research Council Canada. They use the software in cutting-edge design to explore and improve the evacuation safety of complex structures, generating considerable consultancy income. Projects that have used the EXODUS software include the Airbus A330-X, A340 and A380 **[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 **[3b, 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)** The EXODUS software tools give fire engineering firms a competitive edge when bidding for projects, enabling them to win important contracts and generate significant income. Examples during the REF period include global engineering firms Arcadis and Thornton Tomasetti, which used buildingEXODUS, under license, to undertake early design assessments of the life safety and emergency management systems for major projects such as the Opera Metro Station in Antwerp Belgium,

Citmark Building (Lloyds Banking Group), Edinburgh **[5.3]**, a large Data Center in the USA, and a car rental facility at a major US airport **[5.4]**. **(iv)** FSEG research, which led to the development of the ADSS concept **[3f]** has created a new market in emergency signage technology. The ADSS concept improves signage detectability 100%, enabling the sign to adapt to the changing hazard environment **[3.4, 3.8]**, thus bringing the humble emergency sign into the 21st century. Globally, signage manufacturers have adopted and adapted the concept. Two companies, EVACLITE and CLEVERTRONICS, focus on the FSEG ADSS concept. EVACLITE was established in the UK to manufacture and sell ADSS **[5.5]**. CLEVERTRONICS, Australia's leading emergency lighting company, has adopted the ADSS concept and started a new business to develop and manufacture the product **[5.6]**. These two businesses are founded on the FSEG concept, with many other companies around the world adapting similar concepts, all based on FSEG fundamental research.

(2) Impact on Public Policy. (i) While the AASK database was developed primarily to assist the design of aircraft evacuation models, it has also been used to inform international legislation on aircraft safety and airline staffing of cabin crew. For example, in 2011 the FSEG research **[3.1]** was cited in Australian Parliament debates/reports in support of maintaining the number of required cabin crew on Australian registered aircraft **[5.7-5.9]**. The proposed cuts were defeated, and through the current REF period, the number of crew required on Australian passenger aircraft was maintained, helping the Australian aviation industry retain its reputation as the safest in the world. **(ii)** FSEG remains the only research team to collect human factors data defining how quickly passengers respond to evacuation alarms on ships at sea during semi-unannounced drills **[3.11]**. This work demonstrated that the data used in the International Guidelines on Ship Evacuation Analysis in IMO MSC Circ 1033 was incorrect, thus leading to an inappropriate assessment of evacuation capabilities. The data and analysis were accepted by IMO at the 2007 Fire Protection subcommittee meeting (FP51) and included in the revised International Guidelines document, IMO MSC Circ 1238, and the more recent revision (June 2016), IMO MSC Circ 1533 **[5.10]**. During the REF period, the MSC Circ 1533 methodology has continued to be used by maritime engineers around the world as part of the safety certification process for large passenger ships (cruise ships and large ferries), which makes use of modelling data generated by FSEG**. (iii)** 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 **[3g]**, 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 **[3.6]**. 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 **[5.11]**. **(iv) Prof Galea**, one of six experts to the Grenfell Fire Inquiry, provided a report to the Inquiry containing 42 evidence-based **[3.3-3.5, 3.7]** interim recommendations to improve evacuation of residential high-rise buildings **[5.14]**. 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) **[5.15]**. The recommendations aim to improve public safety through regulatory/policy change in the UK.

(3) Impacts on Practitioners and Professional Services. (i) FSEG data incorporated in MSC Circ 1533 are used globally in ship evacuation analysis to demonstrate that passenger ships can be evacuated safely **[5.10, 5.12]**. **(ii)** The new guidelines **[5.11]** for optimal positioning of bollard arrays impacts professional practice through the modification of the previous design practice. **(iii)** A restricted version of EXODUS 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, 3h]**. Using this approach has had a significant impact on how security professionals plan for and

develop counter measures **[5.13]**. **(iv)** Over the REF period, the EXODUS software has been used by over 200 licensees in 30 countries (see 1i). It has become one of the standard engineering design tools for safety analysis, used by fire safety engineers around the world. The software therefore has an impact on engineering professional practice globally **[5.3, 5.4]**.

(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. For example, data on human performance and behaviour collected and analysed by FSEG makes our passenger ships and aircraft safer by improving standards, such as IMO guidelines for passenger ship evacuation (see 2ii), and maintaining cabin crew numbers on aircraft (see 2i); through the introduction of novel concepts in emergency signage, making emergency signs more effective, and buildings safer (see 1iv); by ensuring that security bollards around our infrastructure have minimum impact during emergency evacuation (see 2iii) and through recommendations to improve the safety of residential high-rise buildings (see 2iv). **(ii)** Members of the public make an important contribution to their personal safety, the safety of their families and of society at large. 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. This extends to promoting public understanding of science via the media, helping to build resilience to science scepticism, which the COVID-19 pandemic has highlighted as a growing societal issue. This is achieved through media coverage of FSEG research and interviews with **Prof Galea** on evacuation and pedestrian dynamics. The engagement 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). Explaining the importance of standing on escalators during rush hours in the London Underground: 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 Horizon 2020 project AUGGMED, developing VR training environments for security services: BBC CLICK 28/04/17 (https://bbc.in/3qdBuLW). **Prof Galea** interviews on the Grenfell Tower Fire: BBC Radio 4 Inside Science 15/06/17 (https://bbc.in/3uVOmdg); NYTimes 19/06/17 (831k print subscribers, 4.7m digital news subscriptions). 'U.K. Officials Said Material on Tower Was Banned. It Wasn't', (https://nyti.ms/2yzyDnO); NY Times, 24/06/17 'Why Grenfell Tower Burned: Regulators Put Cost Before Safety', (https://nyti.ms/3qiPeFh): The Economist, (24/07/17) (1.7m global print and digital circulation) 'Tall buildings are becoming more common. They need not be dangerous. With proper enforcement, fire regulations can keep tower-dwellers safe', (https://econ.st/2yFZXR9).

5. Sources to corroborate the impact

1. University of Greenwich sales accounts, EXODUS licence income (Aug 13–July 20)
2. Testimonial: Airbus Chief Engineer, France.
3. Testimonial: Arcadis, Associate Technical Director, UK
4. Testimonial: Thornton Tomasetti, Principal, UK
5. Evaclite: identifies FSEG research incl GETAWAY [3f] https://www.evaclite.com/about-us/; https://www.evaclite.com/directional-safety-signage-systems/
6. Testimonial: Clevertronics Managing Director, Australia
7. Australian Civil Aviation Legislation Amendment Bill 2005, PDF page.16
8. Australian Hansard, No4, 10/05/06, 41st Parliament, page.125, http://bit.ly/15R9qEf
9. Standing Committee on Infrastructure and Communications (Australia), Finding the Right Balance, p 26, http://bit.ly/1arxCv9
10. International Guideline Document, IMO MSC Circ 1533, Annex3, p3,4 - https://bit.ly/3rkHynj
11. Traffic Advisory Leaflet 01/16, 15 Nov 2016, Dept for Transport. http://bit.ly/UKgov-bollards
12. Testimonial: Dir Centre for Int. Cooperation, National Maritime Research Institute, Japan.
13. Testimonial: DSTL, lead for Modelling and Simulation Strategy in the Platform Systems Division, UK
14. Galea E.R., Interim Phase 1 Recommendations for the Grenfell Inquiry - Final, 02/04/19. https://bit.ly/3qkzbXm