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The simulation of urban-scale evacuation scenarios with application to the Swinley forest fire

Anand Veeraswamy[a], Edwin R. Galea[a,*], Lazaros Filippidis[a], Peter J. Lawrence[a], Simo Haasanen[a], Robert J. Gazzard[b], Thomas E.L. Smith[c]

[a] Fire Safety Engineering Group, University of Greenwich, London SE10 9LS, United Kingdom
[b] Forestry Commission England, Bucks Horn Oak, Surrey GU10 4LS, United Kingdom
[c] Department of Geography, King's College London, London WC2R 2LS, United Kingdom

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A B S T R A C T

Forest fires are an annual occurrence in many parts of the world forcing large-scale evacuation. The frequent and growing occurrence of these events makes it necessary to develop appropriate evacuation plans for areas that are susceptible to forest fires. The buildingEXODUS evacuation model has been extended to model large-scale urban evacuations by including the road network and open spaces (e.g. parks, green spaces and town squares) along with buildings. The evacuation simulation results have been coupled with the results of a forest fire spread model and applied to the Swinley forest fire which occurred in Berkshire, UK in May 2011. Four evacuation procedures differing in the routes taken by the pedestrians were evaluated providing key evacuation statistics such as time to reach the assembly location, the distance travelled, congestion experienced by the agents and the safety margins associated with using each evacuation route. A key finding of this work is the importance of formulating evacuation procedures that identifies the threatened population, provides timely evacuation notice, identifies appropriate routes that maintains a safe distance from the hazard front thereby maximising safety margins even at the cost of taking longer evacuation routes. Evacuation simulation offers a means of achieving these goals.

1. Introduction

Forest fires (also referred to as wildfires and bushfires) are an annual occurrence in many parts of the world causing massive damage to the natural and built environments, endangering lives and forcing the large-scale evacuation of entire residential areas and business and industrial facilities. Recent examples include the Fort McMurray fires (The Globe and Mail, 2016) in Canada (May 2016) which extended over an area of 590,000 hectares of Alberta involving over 4000 fire fighters and other emergency personnel and resulted in the loss of 2000 structures, the forced evacuation of 88,000 people and damage estimated at $CAN3.6 billion (Regional Municipality of Wood Buffalo, 2016); the San Bernardino County Blue Cut fires in California (August 2016) involving more than 2600 fire fighters, resulting in the loss of over 100 family residences (Incident Information System, 2016) and requiring mandatory evacuation calls to over 34,000 homes with more than 82,000 people, ranging from a ski resort to the entire town of Phelan with more than 14,000 residents (Chicago Tribune, 2016); and the Hafia Israel fires (BBC News, 2016), resulting in the evacuation of some 80,000 people from homes, schools, kindergartens, universities, a hospital for the aged and prisons (BBC News, 2016 and The New York Times, 2016), police and emergency services went door to door to alert people on the need to evacuate and the affected population evacuated on foot and by car (The New York Times, 2016).

One of the world's worst wildfires in living memory are the Black Saturday bushfires of Victoria Australia (February 2009) which claimed the lives of 173 people, burnt 430,000 hectares of land, 2000 properties and 61 businesses, with an estimated cost of $AUS4 billion (Teague et al., 2009). Rather than a single fire there were over 47 fires scattered across the State that had the potential to become severe, five of which claimed people's lives – the most costly was the Kilmore East fire that claimed 119 lives. The Country Fire Authority (CFA) engaged approximately 12,000 CFA fire fighters and over 1000 operational vehicles to fight the fires with the support of an additional 1000 fire fighters from the Department of Sustainability and the Environment (DSE). One of the issues to come out of the Royal Commission held to investigate the response to the fires concerned the advice given to the community on whether or not they should evacuate, the so-called 'stay or go' policy, more correctly stated as, 'Prepare, Stay and Defend or Leave Early'. The Commission concluded that the authorities had

* Corresponding author.
E-mail address: e.r.galea@gre.ac.uk (E.R. Galea).

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placed insufficient emphasis on the risks of staying and defending ones property and that the safest option is always to leave early. The Commission recommended that, '… the State introduce a comprehensive approach to evacuation so that this option is planned, considered and implemented when it is likely to offer a higher level of protection than other contingency options ……' (Recommendation 5) (Teague et al., 2010).

The threat posed by wildfires is not restricted to countries with hot climates. A large number of wildfires occur in Great Britain every year. In the past four years there have been on average 45,000 wildfires each year attended by the fire and rescue services in Great Britain (Crowhurst, 2015). Furthermore, warmer and drier conditions, and more frequent and longer-lasting heatwaves also raise the risk of wildfires. This risk is compounded by the UK's high population density, which means that fires are more likely to encroach into urban environments, posing a significant threat to life. Forest fires can spread rapidly affecting built-up areas in its path at different times depending on the speed and direction of the fire spread, which in turn is dependent on a number of factors such as the wind speed and direction, nature of terrain and available fuel in the path of the fire (BBC News, 2016; Chicago Tribune, 2016; Regional Municipality of Wood Buffalo, 2016; Teague et al., 2009, 2010; The New York Times, 2016).

It is clear that wildfire often requires the evacuation of large numbers of people from large areas and potentially over great distances. The frequent and growing occurrence of these events suggests that it is necessary to develop appropriate evacuation plans for areas that are susceptible to wildfires.

This paper provides an overview of the development of the EXODUS urban-scale evacuation modelling system (Chooramun et al., 2012; Galea et al., 2008, 2011; Pretorius et al., 2013 and Siddiqui and Gwynne, 2012), and describes the application of the software to a case study involving the Swinley Forest fire that occurred near Bracknell in Berkshire, UK on May 02, 2011. As part of this work, the paper also describes the loose coupling of the EXODUS software to the Prometheus wildfire simulation tool (Tymstra et al., 2010). It is suggested that the developed methodology could be utilised by authorities to formulate evacuation procedures before an incident takes place based on historic data (e.g. past wildfires, floods, earthquakes, etc.) and also has scope to be applied during incidents by providing first responders with key evacuation related information.

2. Literature review

When planning an evacuation for a community threatened by wildfire, it is essential for civil protection authorities to know what areas will be affected due to a fire, when the areas will become untenable, how long it will take occupants in these regions to evacuate and how long it will take occupants to reach a designated place of safety. To this end, fire simulation tools such as Prometheus (Tymstra et al., 2010) and Phoenix (Tolhurst et al., 2008) have been developed that attempt to predict the spread of the wildfire. These models take into consideration the nature of the available fuel, the terrain and the atmospheric conditions and provide an estimation of the direction and rate of spread of the fire front.

While this type of information is necessary to assess the level of risk associated with each region it is not sufficient to optimally determine how and when to warn the population appropriately, how to allocate available resources (first responders, fire fighters and staff at assembly locations) and most importantly to formulate an effective evacuation strategy which involves safe routes that occupants can take to the designated assembly locations. To do this also requires an ability to predict the evacuation movement and behaviour of city sized populations of people measuring in the tens of thousands if not hundreds of thousands.

Several evacuation models have been developed that attempt to simulate large scale evacuation situations resulting from floods (Durst et al., 2014) and earthquakes (D'Orazio et al., 2014). MATSIM, a transport simulation tool has been used to perform pedestrian evacuation simulation at city scale involving over a million agents (Lämmel, 2008). The road network is imported from OpenStreetMaps (Neis et al., 2011) and represented in MATSIM as a directed graph with the streets being represented as links or arcs connecting the vertices or nodes, which represent a point on the earth's surface. Network change events such as altering the state of a link from traversable to non-traversable occurs dynamically as the simulation runs. Initially all agents utilise a shortest path to the refuge areas. However, the Nash equilibrium (Osborne and Rubinstein, 1994) approach is employed where agents attempt to find a route that is optimal in terms of the time required to reach the destination in each successive iteration taking into account congestion levels encountered on the evacuation routes. Over many iterations this approach provides an estimation of the overall shortest evacuation time which could represent an evacuation where agents have been trained or guided so as to follow a pre-determined procedure. This approach has been used to model the pedestrian evacuation simulation of the entire city of Padang, Indonesia involving 320,000 agents in response to a tsunami (Lämmel et al., 2010) and a part of Zurich involving 165,571 agents in response to a flood (Lämmel, 2008). A similar approach has been used to model large-scale multi-modal (i.e. involving pedestrians, buses, railway and cars) evacuation simulation of Hamburg-Wilhelmsburg, Germany consisting of 50,601 inhabitants in response to a flood (Klüpfel, 2014). Travel mode change options were also implemented allowing for example agents to walk to a bus stop, take a bus to the train station and take a train to a safe location.

The PedGo simulation tool has been used by (Klüpfel, 2014) to perform pre-event and post-event pedestrian simulations of a popular event that attracted a very large number of visitors (250,000) in Burgdorf, Switzerland. The actual pedestrian traffic flow and congestion observed during the event was significantly different (less congestion was observed than predicted) from the pre-event simulations mainly because of an underestimation of response times and overestimation of the number of people. When these factors were modified accordingly the post-event simulations provided a good agreement with the observations during the actual event. This illustrates the intricacies in large scale evacuations – small deviations from assumptions of initial conditions can lead to large differences in the simulation results when compared to the actual event.

The simulation of large-scale evacuation requires the inclusion of a number of human behaviour aspects into the modelling process. According to (Osaragi et al., 2013) the following factors are key to model large scale evacuations following an earthquake: spatiotemporal distribution of people at the time of the earthquake, time at which people start evacuating, decision to head to a temporary refuge location or to the official refuge location and routes that people choose to use (familiar versus safe routes avoiding affected areas). A study of human behaviour during earthquakes, both within structures and outside, (Bernardini et al., 2014) has identified the following behaviours; attraction to safe areas, herding behaviour, attraction between members of the same group, keeping a safe distance from buildings and group formation. They also determined the average speeds and distances between members of the same evacuating group and represented these behaviours in a simulation tool by modifying the social force model (Helbing and Johansson, 2013).

A city scale evacuation model utilising a potential map system for navigation has been developed (Nishino et al., 2011) where agents travel towards refuge locations taking paths that they perceive to be safe while staying away from hazards such as fire. A flood simulation model was coupled to an evacuation simulation model (Mordvintsev et al., 2012) where agents could assume one of several states such as idle, running, safe and drowned. Agents followed a potential map avoiding static obstacles as well as non-traversable flooded areas to reach safe refuge areas.

While several wildfire evacuation models have been developed