European Journal of Operational Research 241 (2015) 763–770

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Stochastics and Statistics

Using discrete event simulation cellular automata models to determine multi-mode travel times and routes of terrestrial suppression resources to wildland fires

Thomas J. Duff[a,b,*], Derek M. Chong[a,b], Kevin G. Tolhurst[b,c]

[a] Department of Forest and Ecosystem Science , Melbourne School of Land and Environment, The University of Melbourne, Burnley, Vic, 3121, Australia
[b] Bushfire Cooperative Research Centre, East Melbourne, 3002, Australia
[c] Department of Forest and Ecosystem Science, Melbourne School of Land and Environment, The University of Melbourne, Creswick, Vic, 3363, Australia

ARTICLE INFO

Article history:
Received 31 July 2013
Accepted 16 September 2014
Available online 28 September 2014

Keywords:
Transport
Network
OR in environment and climate change
Routing
Simulation

ABSTRACT

Forest fires can impose substantial social, environmental and economic burdens on the communities on which they impact. Well managed and timely fire suppression can demonstrably reduce the area burnt and minimise consequent losses. In order to effectively coordinate emergency vehicles for fire suppression, it is important to have an understanding of the time that elapses between vehicle dispatch and arrival at a fire. Forest fires can occur in remote locations that are not necessarily directly accessible by road. Consequently estimations of vehicular travel time may need to consider both on and off road travel. We introduce and demonstrate a novel framework for estimating travel times and determining optimal travel routes for vehicles travelling from bases to forest fires where both on and off road travel may be necessary. A grid based, cost-distance approach was utilised, where a travel time surface was computed indicating travel time from the reported fire location. Times were calculated using a discrete event simulation cellular automata (CA) model, with the CA progressing outwards from the fire location. Optimal fastest travel paths were computed by recognising chains of parent–child relationships. Our results achieved comparable results to traditional network analysis techniques when considering travel along roads; however the method was also demonstrated to be effective in estimating travel times and optimal routes in complex terrain.

1. Introduction

Periodic forest fires are a part of natural processes in many parts of the world (Fuller, 1991; Mooney & Dunn, 1970). Where fires burn into populated areas, they have the potential to cause substantial impacts, including the loss of assets, productivity and lives (Mendes, 2010). As a result, fire suppression activities are typically implemented to minimise such impacts (Martell, 1982). Such activities involve the use of specialised vehicles, crews and aircraft (hereon described as resources) to directly extinguish flames or prevent further fire spread. Suppression has been demonstrated to be effective in reducing the sizes and consequential costs of fires. In particular, the sooner suppression resources arrive at a fire, the smaller the resultant impact is likely to be (Cumming, 2005; DeWilde & Chapin, 2006).

Inherent stochasticity in the initiation of forest fires results in uncertainty as to where and when future ignitions will occur (Dayananda, 1977). Consequently, fire suppression is reactive; resources are dispatched from home base locations as fires are detected (Kourtz, 1987). As the time that elapses between fire detection and resource arrival is directly correlated with the final fire sizes, an understanding of emergency vehicles response times is critical for optimising deployment decisions and planning efficient suppression (Haghani & Yang, 2007). In addition, the suppression algorithms in operational dynamic fire spread simulators (including FARSITE (Finney, Sapsis, & Bahro, 2002) and PHOENIX Rapidfire (Tolhurst, Shields, & Chong, 2008)), require detailed information on available suppression resources to be manually specified. Consequently, the automation of the process of determining resource availability and likely arrival times of suppression resources at a fire location has the potential to yield gains in suppression efficiency. At a strategic level, the optimisation of the placement of resource bases has long been a major focus of operational research (Li, Zhao, Zhu, & Wyatt, 2011). Vehicle response times are a key input required for such models (Badri, Mortagy, & Alsayed, 1998), and if such inputs do not accurately consider all necessary travel, outcomes may be sub-optimal. The determination of

* Corresponding author at: Department of Forest and Ecosystem Science, Melbourne School of Land and Environment, The University of Melbourne, Burnley, Vic, 3121, Australia. Tel.: +61 418 552 726; fax: +613 5321 4166.
E-mail addresses: tjduff@unimelb.edu.au (T. J. Duff), derekmoc@unimelb.edu.au (Derek M. Chong), kgt@unimelb.edu.au (Kevin G. Tolhurst).

http://dx.doi.org/10.1016/j.ejor.2014.09.019
0377-2217/

the shortest, fastest or most efficient paths through networks has long been a focus of graph theory and operational research (Prodhon & Prins, 2014). Dijkstra's algorithm (Dijkstra, 1959), was a major development in this field, providing a foundation for much of the work that followed (Sniedovich, 2006). Variants of Dijkstra's algorithm are commonly used to estimate the routes and probable travel times for vehicles in road networks (Zhan & Noon, 1998). Such algorithms 'crawl' through vector networks, accumulating costs, such as distance or time, as they progress between nodes to determine the least-cost path between a start point and destination.

However, the need to estimate travel times and routes to forest fires provides an additional level of complexity; fires often occur in isolated areas and require substantial cross country travel where movement is independent of the road network. The vegetation and terrain properties that affect cross country travel are typically heterogeneous and information dense, and consequently are more efficiently stored as raster grids than vector networks. In contrast to the development of methods for optimising road network travel, there has been relatively little consideration given to the problems where vehicles may have to travel both on and off road. Multi-model travel has been considered in mixed vector networks, such as those that include road and rail travel (Bielli, Boulmakoul, & Mouncif, 2006), but there has been limited attention in raster landscapes. Hatfield et al. (2004) proposed a combined method for estimating both road and cross country travel times for fire suppression vehicles in a gridded landscape using a minimised accumulated cost surface approach (Douglas, 1994), where costs are specified as the time to cross a unit of space. Pathfinding algorithms, including Dijkstra's algorithm, can be used to accumulate weighted costs based on travel between grid cell centroids (Geitl, Doneus, & Fera, 2008; Soltani, Tawfik, Goulermas, & Fernando, 2002). Such approaches have been used in the generation of least cost routes in continuous terrain; however their application for real-time travel planning remains experimental (Dalton, 2008; Hatfield et al., 2004; Stahl, 2005).

The simulation of a chronological sequence of events occurring within regular grid is highly amenable to analysis via discrete event simulation (DEVS) cellular automata (CA) approaches (Wainer & Giambiasi, 2001). Such models have been successfully used in modelling physical systems and processes and have been used in relation to fire management for simulating fire spread and suppression activities (Ameghino, Troccoli, & Wainer, 2001; Ntaimo, Xiaolin Hu, & Yi Sun, 2008). We propose an alternative, novel framework for the determination of multimode estimated vehicular travel times and optimal routes to fires using a DEVS CA emulation of Dijkstra's algorithm in a gridded raster landscape. The method is intended to be processed in real time (once a fire location is reported) and provides output as a surface of travel times to the fire location within a specified period. Parent–child relationships between adjacent cells are retained to allow the identification of the fastest routes from each point in the landscape to the fire location. Our approach provides for the use of heuristic rules within the CA, allowing processing times to be minimised by reducing unnecessary calculations.

The method is demonstrated using example fire locations and resource bases situated in the vicinity of the Black Saturday fires that occurred in Victoria, Australia in 2009. The Black Saturday fires were Australia's worst ever forest fire disaster, with 173 people killed and over 2200 buildings destroyed in less than 12 hours (Cruz et al., 2012).

2. Material and methods

2.1. Theory/analysis framework

The generation of maps of 'travel catchments' of road travel time for resource bases is common practice in emergency response analysis, as response times to each point in the road network can be pre-processed (Li et al., 2011). However, due to the data dense nature of raster grids, the storage of such response times for all points in the landscape is inefficient, particularly where multiple bases are considered. In addition, such an approach has an inherent assumption that all dispatching occurs from fixed locations, however in the event of multiple incidents it may be necessary to redeploy vehicle in transit. We propose that the problem be reversed and computed on demand. Rather than calculating travel times outwards from bases, travel times be computed outwards from a point of interest (such as a fire) for a specified distance or duration.

A DEVS CA cost accumulation approach was developed to estimate vehicle travel times to a point of interest in a continuous raster landscape. The landscape is defined by a raster grid with the value of each cell representing the time it takes for a vehicle to cross a unit of space; the travel cost. The CA algorithm crawls out from the point of interest calculating expected travel times by multiplying the cellular travel cost by distance travelled estimated at travel times from every cell to the source point are calculated by tallying the total time the taken to reach that cell; the accumulated travel time (ATT). The ATT raster remains aligned with the unit travel cost input grid. The algorithm spreads in all directions at rates proportional to the travel cost. Consequently the ATT values are indicative of the fastest time to reach a cell in the landscape from the point of interest. The pattern of spread is indicative of the fastest path to reach a landscape cell from the point of interest. Travel times for suppression vehicles to the point of interest can be determined by using their coordinates to query ATT raster. By retaining parent–child data from the CA spread algorithm the fastest route from the point of interest to each cell in the ATT raster can be evaluated.

2.2. Generation of unit travel time raster

For travel time estimation, a unit travel time cost surface for the entire state of Victoria (22.7 million hectares), Australia was developed as a 30 meter grid. This was created by merging two unit travel time rasters, one generated from a road network layer and another generated from classified vegetation types. For computational efficiency, units were specified in terms of milliseconds/meter^{-1} to allow calculations to be processed as 16 bit unsigned short integers.

Road data was obtained as categorical vector networks where roads were classified by road class. Estimated average travel speeds in kilometers/hour^{-1} for each class were obtained from the Department of Environment and Primary Industries (DEPI), Victoria, and these were reciprocated and converted to milliseconds/meter^{-1} (Table 1). A class based join was used to specify unit travel time for each mapped road segment of the vector road layer. This was converted to a 30 meter raster, using the unit travel times as values. Grid cells that did not coincide with parts of the road network were given 'no-data' values.

Unit cross county travel times were estimated using vegetation types mapped at a 30 meter resolution. Vegetation maps were based on a statewide DEPI vegetation classification intended for the representation of vegetation communities and fire fuel loads. These were condensed into broad categories based on vegetation structure and

Table 1
Travel speeds by road class.

Road class	Road type	kilometers/hour^{-1}	milliseconds/meter^{-1}
0	Freeway	90	40
1	Highway	80	45
2	Arterial	70	51
3	Sub-arterial	70	51
4	Collector	60	60
5	Local road	40	90
6	2WD unsealed road	40	90
7	4WD unsealed road	20	180