Urban structure and evacuation times in a city fringe bushfire: modelling three scenarios in Bendigo, Victoria

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Abstract: Urban fringe residential development is a common practice in Australia, increasingly located in bushfire-prone areas. This vulnerability condition may lead to bushfire disasters; in this case, evacuation is deemed as an effective risk reduction strategy, as stated by the AFAC's 'stay and defend, or leave early' policy. For emergency planning purposes, it is critical to estimate the range of times involved in the evacuation of a community, and the factors that might influence it. This paper addresses this issue with a particular emphasis on spatial configuration. It aims to evaluate (1) the total required evacuation time for a given urban fringe community during a bushfire; (2) the way urban structure characteristics affect that time; and (3) the emergency management policy implications related to those findings. To achieve this, an agent-based computer model is used to analyse three small-scale case studies in Bendigo, Victoria. The results show that a complete evacuation takes considerable time (between 30 minutes and 1 hour), despite spatial different sizes and urban patterns, and that it is possible for bushfires to overrun or surround settlements before people leave following a warning. This confirms the 'leave early' policy as appropriate, if adequately supported by timely warning systems with a high degree of penetration across the population. Certain urban structure characteristics, such as urban density, appear to have an impact on the total evacuation time. By enhancing the model with further case studies and evacuees' behavioural characteristics, evacuation-based comprehensive design standards for urban fringe areas could be developed.

Introduction

The rate of residential development in urban fringe areas is growing in Australia, attracting dwellers seeking its mix of wildlife, larger lots, and apparently lower costs. However, as growth augments in peri-urban and rural areas, new developments incrementally increase their risk of being affected by a naturally occurring or human-made bushfire, an ever present phenomenon in the Australian environment. In some occasions, bushfires can turn into severe disasters, provoking substantial losses of lives, wildlife features, and material assets.

Australia has a long tradition of dealing with bushfires, since its first inhabitants. Several academic and governmental efforts have been conducted in increasing theoretical and practical knowledge about bushfires and their specific characteristics as disasters. There is growing understanding of the physical parameters that determine how a fire starts, spreads and ends in the wild; and recent approaches have been conducted to understand how bushfire interacts with the urban physical elements in fringe areas (see for instance March et al., 2011).

As a key strategy for coping with disasters, bushfire evacuation in Australia has been the subject of several studies and planning approaches. These efforts have been conducted especially in terms of the behavioural characteristics of evacuation as a response to a bushfire threat, and the aftermath of this in terms of survival (Krusel and Petris 1992, Handmer and Tibbits 2005). Recent approaches have started to integrate into computer simulations the evacuees' behaviour, including the environmental factors that would affect evacuation, such as road maps and fire profiles. This has been undertaken with the aim of supporting multiple stakeholders' decision-making processes in emergency planning (Scerri, Hickmott et al. 2012).

This line of enquiry shows that it is critical to estimate the range of times involved in evacuation processes if that is chosen as an effective risk reduction strategy: prediction, response, warning, and evacuation (Opper 2004). While the three first steps of this process rely on an authority such as policy or emergency services, the latter is strongly based on occupants' self-responsibility and ability; therefore it is important to estimate the actual time that a given community in a threatened condition would spend in an evacuation, and the factors that might influence that process.

This paper takes a first step in the direction of determining whether evacuation is a valid approach in a given location in an urban fringe area, with a particular emphasis on spatial configuration. It aims to respond to three main questions: (1) what is the required total evacuation time for a given community in an urban fringe area during a bushfire emergency? (2) How do urban structure characteristics affect that time? (3) How do current emergency management policies accord to these evacuation scenarios? To achieve this, three case studies in Bendigo, Victoria, are examined; they are small size developments, i.e. around 500 dwellings, a common pattern in Australian urban fringe areas. The cases will be examined through an agent-based model developed in Agent Analyst, an open-source extension for ArcGIS. This model incorporates characteristics from the evacuees and the urban realm to determine the outcome of an evacuation during a bushfire emergency.

The first part of the paper introduces a theoretical background that includes disaster risk management and evacuation as a response activity, with bushfires as a specific disaster type to study. In part 2 of the paper the method is presented, including the three case studies sites, the characteristics of the emergency scenario proposed, and the agent-based model to run the experiment. Part 3 introduces the results of the model. Part 4 presents a discussion of the results, and part 5 presents the main conclusions.

Background

Disaster risk management

Disasters can be defined as traumatic and stressful events, concentrated in time and space, which seriously disrupt the normal functioning of a community or society, provoking large human, material, economic or environmental losses (Alexander 1991, UNISDR 2009, Nicholls 2010). Pearce (2003) argues that the disaster management field originated as a response to the nuclear threat in the mid-20th century, but afterwards the natural environment was identified as the main source of harm to mankind. In recent decades, there is a growing consensus in understanding that disasters have their origins in existing cultural, social, political, and economic conditions, instead of in nature (Alexander 1991, Blaikie, Cannon et al. 1994, Mileti 1999, Pelling 2003). Oliver-Smith (2002: 24) argues that "disasters come into existence in both the material and the social worlds and, perhaps, in some hybrid space between them".

This shift of emphasis has influenced the tactics for coping with disasters, which have changed their focus from reactive relief approaches, to proactive and comprehensive risk-reduction strategies (Pearce 2003, UNISDR 2004, Tarrant 2006). Modern disaster management comprises four main

actions, performed cyclically in time, before, during, and after the event: mitigation (i.e. reducing the likelihood or consequences of a hazard), preparedness (i.e. actions to minimize impacts, under unaltered risk and vulnerability circumstances), response (i.e. actions to cope with the ongoing disaster), and recovery (i.e. return to victims' normal life prior to the catastrophe, creating new opportunities for development) (Coppola 2011, Topping 2011).

It is important to note that every disaster is different. Berren et al. (1980) propose a five-dimensional disaster typology, based on: (1) type (naturally originated or man-made); (2) duration; (3) degree of personal impact; (4) potential for occurrence (recurrence); and (5) control over future impact. Disasters managers must pay close attention to these differences, for developing the best possible strategies for dealing with the events. For instance, earthquakes and bushfires have their origins in natural processes, and are rapid onset events, with potentially high degrees of impact on humans. However, whilst earthquakes may affect areas hundreds of kilometres wide, bushfire impact is usually constrained to more specific areas. Also, the former has a recurrence period of decades, whilst the latter can be yearly phenomena. Despite these differences, in both cases control measures can be developed for reducing future impacts, e.g. through improved building codes or land-use regulations.

Evacuation as a response to disaster

Evacuation can be defined as "the withdrawal actions of persons from a specific area because of a real or anticipated threat or hazard" (Vogt and Sorensen 1992: 3) . It has to be performed when there is a large number of persons in a hazard situation, with an actual or perceived threat to their lives, and a subjective but time-limited possibility of escape (Drury and Cocking 2007). Evacuation can be examined as a planning problem, which implies three main issues: who is at risk, how long will it take to evacuate, and how much time is available (Cova, Dennison et al. 2005). Another key determinant, evacuee behaviour, is conditioned by three main factors (Mohareb 2011): (1) social behaviour (e.g. collaboration vs. panic); (2) spatial behaviour (e.g. the selection of escape routes); and (3) evacuation required times (e.g. warning response, departure, travel to safe locations, etc.).

Evacuation planning is highly related with the characteristics of the existing arrangements of urban places' physical features. This dimension is examined by the discipline of urban design, which usually deals with the scale between built structures (e.g. dwellings) and settlement patterns (March, Holland et al. 2011). Urban design has had an historic role in achieving urban safety, especially on avoiding, mitigating, and preventing natural hazards (Cai and Wang 2009). In turn, the spatial form of a city can positively influence the speed and effectiveness of responses to major disturbances (Allan, Bryant et al. 2013). In disasters where a rapid evacuation is required or is to be considered as an option, such as in bushfires and tsunamis, urban design has a key role in providing an adequate egress, i.e. a means of exiting an evacuated area (Cova 2005).

Evacuation modelling

Computer-based modelling has become a powerful tool to assess crowd movement and large evacuation processes, within built spaces and open urban areas. Two main types of urban evacuation models can be distinguished: static and dynamic. The former examines the influence of the environment on the evacuees' speed, whilst the latter focuses on evacuees' internal factors, then models them as individual agents (Imamura, Muhari et al. 2012).

Agent-based modelling is "a powerful modelling technique for simulating individual interactions and capturing group behaviour resulting from individual interactions in a dynamic system" (Chen and Zhan 2008: 25). It allows complex systems to be disaggregated into units (the agents), each of them following a set of rules (i.e. an algorithm) to interact between themselves and with a representation of their environment (Klüpfel 2003). The outcome of this process is called emergent or collective

behaviour, which allows to calculate the required time to evacuate all agents from and endangered area; it is the result of the individual decisions of them (Chen and Zhan 2008, Lämmel, Rieser et al. 2010, Johnston 2013).

Bushfires in Australia

Bushfires have been a part of Australian natural environment for thousands of years; its original inhabitants, forests, and grasslands have evolved to adapt to these phenomena. This relationship was altered by the arrival of European settlers, which started "an uneasy relationship between people and fire in the landscape…many have lost their lives and homes, business and community infrastructure have been destroyed and the ecosystem damaged by intense bushfire" (AFAC 2012: 1). During the 20th century in Australia, bushfires were the fourth most dangerous natural hazard in terms of human casualties, after heatwaves, cyclones, and floods (Coates, 1999, quoted by Haynes, Handmer et al. 2010).

People at risk from a bushfire attack have three options (Handmer and Tibbits 2005): (1) evacuate well in advance; (2) prepare themselves and their property, and stay; and (3) leave at the last moment, when the fire is arriving. Evidence collected from 20th century archives (prior to the 2009 Black Saturday fires) showed that staying and defending a dwelling was the safest option, whilst leaving at the last moment was the most dangerous (Haynes, Handmer et al. 2010). Cova et al. (2009) argue that staying might be an option when exit roads are blocked by fire, when evacuating is perceived as too risky, or when residents want their dwellings to survive the bushfire. Before the 2009 Black Saturday fires, the community safety policy from the Australasian Fire and Emergency Service Authorities Council enforced the 'stay and defend your property, or leave early' strategy (AFAC 2005). An updated version of this paper (AFAC 2012) emphasizes the 'leave early' option as the safest action, whilst evacuating in front or during the passage of a bushfire is deemed as a highly risky activity. Sheltering is a part of a broader strategy to mitigate bushfire impact, including managing fuels and preparing a survival plan.

An important aspect of early evacuation is the need for appropriate warning mechanisms. Victoria's Central Fire Authority (CFA) warning system has three levels, each increasing in importance (CFA 2013): advice, watch and act, and emergency warning. A released warning can be found in the CFA website, the Victorian Bushfire Information Line, radio and television, social networks (Twitter, Facebook), and in mobile phones apps. In extreme circumstances, the Emergency Alert system may send telephone warnings directly to landlines or mobile phones. CFA urges people to not rely on an official warning to leave.

Method

Three case studies in Bendigo

Bendigo is a city of some 140,000 inhabitants, located approximately 140 km northwest of the Victorian capital, Melbourne. Much of its recent residential development has been located in fringe bushfire-prone wildlands; usually these areas are selected because they provide easy access to recreation, panoramic scenery, and lower property costs (Cova 2005). The bushfires of the 7th of February 2009 seriously affected this urban fringe (as close as times as only 2 km away from the city centre). The fire commenced after 4:00pm, travelled 4.7 kilometres in a south easterly direction driven by gusty winds averaging 41 kilometres per hour. The fire occurred in grasslands and the crowns of trees, with high ignition rates also facilitated by the very low relative humidity of 6%. Ember spotting occurred up to 2 kilometres in advance of the fire's front (Teague, McLeod et al. 2010). To complicate matters, the fire was then driven in a north easterly direction when the wind changed to the south west at 35km/h at approximately 6:30pm. This resulted in a four kilometre fire front, which challenged the

capacity of response agencies. The fire was largely contained at approximately 7:30pm, when the main part of the fire was considered under control and mopping up operations continued. One fatality, 41 injuries, and 341 hectares were burned, and 58 houses were destroyed, with many more homes and properties damaged (Teague, McLeod et al. 2010). The background conditions lead to the fires included over ten years of drought and over one month of record-breaking summer temperatures (Bushfire CRC 2009).

For this research, three case studies in West Bendigo were selected. They are small to medium size residential areas, with recognizable boundaries, located in bushfire-prone zones (see Figure 1 and Figure 2). Case 1 (252 dwellings, approximate area of 74.5 ha.) and 2 (369 dwellings, 168 ha.) are located in the suburban area of Maiden Gully, 7 km west of the CBD. This area has experienced significant growth in recent years; between the 2006 and 2011 censuses its population increased by 36.4%, a much higher rate than the rest of Bendigo (6.6%) (ABS 2013). Case 3 (400 dwellings, 47.3 ha.) is located only 2 km northwest of the CBD, and was affected by the 2009 fires. Based on the typology proposed by Marshall (2005), the street pattern arrangement of the three cases is a 'distributory' one, characterized by a clear impression of a hierarchical structure, access only to minor roads, and many culs-de-sac; its typical location is peripheral developments (see Figure 1and Figure 2). According to the urban density measure proposed by Cova (2005) for communities located in the urban-wildland interface (i.e. road length per household), case 3 exhibits a density level that is 24% greater than case 1, and 35% greater than case 2 (see Table 1).

Figure 1: case studies, West Bendigo. Source: the authors, based on Google Earth image.

Figure 2: detail of case studies, Bendigo, including exit points. Source: the authors, based on Google Earth and Street View images.

Emergency scenarios

Prior to developing the evacuation model for this study, several assumptions had to be made for the emergency scenarios. First, it was assumed that all the dwellings had to be evacuated. Second, the whole evacuation was car-based, with each evacuating household using two vehicles (according to the load factors for residential areas proposed by Cova (2005)). Third, each dwelling fled to its closest exit (i.e. a connection point to a main exiting road), using the shortest possible route (this is a feasible choice in a small community well-known by its inhabitants). Fourth, the evacuation speed was set at 20 km/h (according to narrow existing roads and with visibility hindered by smoke, typically also under strong wind conditions). The fifth assumption included the expected departure time for evacuees after warning; based upon the work of Cova and Johnson (2002).

For the purposes of evacuation, a time 'zero' can be established "when an evacuation order is issued or when community perceives the hazard as a threat" (Cova and Johnson 2002: 2217). From this time 'zero', the departure time (i.e. when evacuees leave the household) will vary across evacuees: few are likely to depart immediately; numbers will then increase over time to a peak; and then will gradually diminish. Cova and Johnson (2002) argue that a common approach to model this behaviour is a cumulative distribution. For achieving this, they propose a Poisson distribution, which "describes the probability of *n* events occurring within a given time period" (Cova and Johnson 2002: 2217), as in this case when a departure time is independent from previous departure times. A discrete Poisson distribution allows estimation of the percentage of departures for each discrete time period (0-5 minutes, 6-10 minutes, etc.) after the time 'zero', according to a single parameter: the mean vehicle departure time (Cova and Johnson 2002). To incorporate a degree of uncertainty, in this case five mean departure times were tested independently: 10, 15, 20, 25, and 30 minutes, each affecting the total evacuation time for the community (see Figure 3).

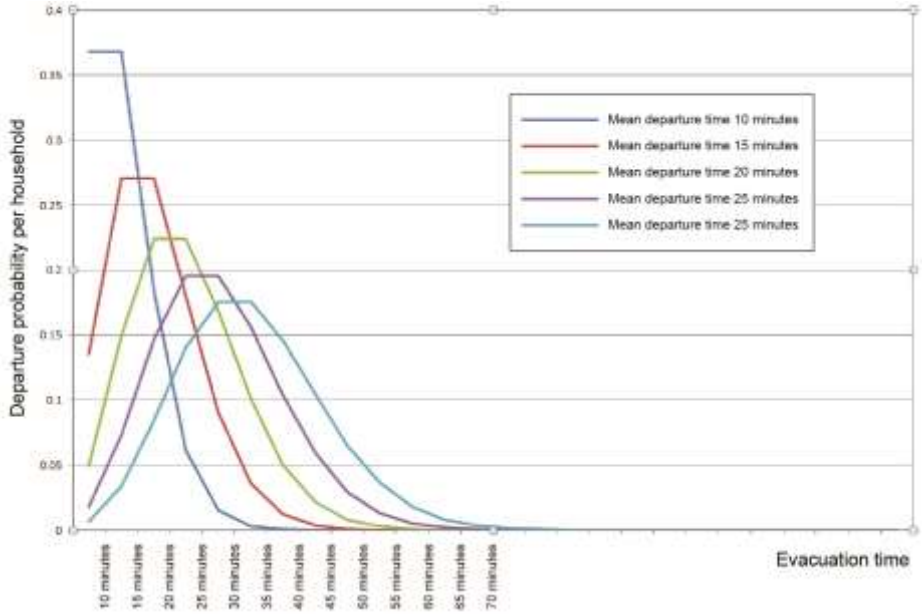

Figure 3: Poisson distributions of departure probabilities per household, for different mean values. Source: the authors.

Finally, for each case study typical disaster scenarios likely to be experienced in a fire scenario were tested, assuming that at least one exit was lost due to surrounding conditions being hazardous (i.e. proximity to fire or an actual burn-over). Therefore 10 tests were conducted for each community: 5 in a 'normal' emergency, and 5 in 'disastrous' conditions.

Model

The model was developed in Agent Analyst (*http://resources.arcgis.com/en/help/agent-analyst/*), an open-source software package aimed at incorporating Repast (an agent-based modelling platform) within a GIS environment (in this case, ArcGIS) (Johnston 2013). Agent Analyst is a "mid-level integration that takes advantage of both modelling environments" (Johnston 2013: 3). This integration is a key feature, because usually (as in this research) the location of the agents and the characteristics of their environment will strongly determine the emergent properties of the model; GIS "stores, displays, and analyses data on spatial relationships" (Johnston 2013: 3).

The model was adapted from that proposed by Groff and Fraley (2013). First, within the GIS environment, the street pattern from each of the case studies was processed into a representative network of nodes -when moving agents along a street network, this is "a very computationally efficient method" (Groff and Fraley 2013: 208). The second step was to create a model in ArcGIS' Network Analyst extension (ESRI 2013), including these nodes, the dwellings, and the exit points for each case. Then Network Analyst allowed the calculation of the shortest routes from each of the dwellings to its closest exit. As Groff and Fraley (2013) point out, developing this routing calculation outside Agent Analyst steeply reduced the processing time. The third step was to convert the evacuation routes into sequences of nodes that could be travelled by the agents. Finally, in the model within Agent Analyst, each evacuee agent (i.e. single dwellings, with 2 cars each) was provided with an escaping route, a departure time (from the aforementioned Poisson distribution) and a travelling speed, plus traffic congestion conditions.

As mentioned above, for each case study 10 tests were conducted. During each of these tests, in turn, the model was run 30 times, to ensure statistical reliability (Cova and Johnson 2002). Each time the model ran, every household was randomly assigned with a departure time from the Poisson distribution, but the mean departure time for the group of dwellings was constant, as established by the Poisson parameter (i.e. 10, 15, 20, 25, or 30 minutes). During each step from each run, after leaving their dwellings, evacuating agents approached the closest exit point. The number of saved evacuees (i.e. when they reached an exit point) was recorded during each step of the model (see Figure 4). A run was completed when every evacuee was safe, and the total required time was recorded. After 30 runs, an average expected total evacuation time for the community is obtained (see Table 1).

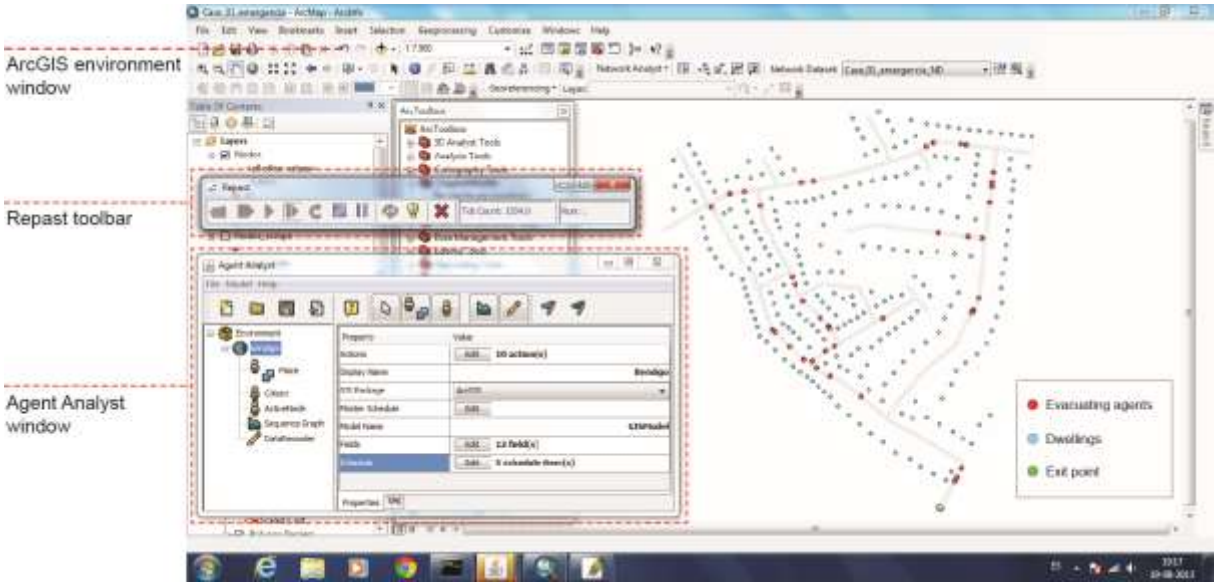

Figure 4: screenshot from the model, for an emergency situation in case 01. Source: the authors.

Results

Table 1 shows the minimum required times for complete the evacuation of each of the three studied communities, according to the aforementioned assumptions. As expected, the departure time has the strongest impact on the overall evacuation time. A first noticeable fact is that a 'realistic' departure time distribution (such as the Poisson one) implies that even relatively small communities may require an important amount of time to be completely evacuated (at least half an hour), although each evacuation trip can be completed in just a few minutes (between 1 and 8, approximately). Despite this, the model shows that an early evacuation is strongly encouraged, because as the mean departure time increases, its relative impact on the total evacuation time diminishes. When the mean departure time approximates to 30 minutes, the total required evacuation time converges to 60 minutes, in all the cases. This occurs because with higher mean values the Poisson distribution tends to have a Gaussian symmetrical shape instead of a skewed one (as pointed out by Cova and Johnson (2002)), with departure times distributed from approximately 0 to 60 minutes (see Figure 3). In this case, times required for the actual displacements from the dwellings to the exit points have a relatively low impact on the total required evacuation time.

To assess the impact of the urban structure on the total evacuation time and to diminish the influence of aforementioned Gaussian effect, a 'cross-section' with a mean departure time of 10 minutes can be examined. For each case, the urban structure characteristics are represented by the number of households, the overall area, the number of exits, and an urban density measure proposed by Cova (2005): road length per household. The 'cross section' shows that, in normal conditions, case 3 requires the longest evacuation time (32.8 minutes), despite the fact that it has the smallest area (47.3 Ha.), the highest number of exits (5), and that its dwellings have the shortest routes to travel (see Table 2). The comparatively higher urban density of this case (15.38 meters of road length per household) might imply that traffic congestion is hindering the fluid movement of evacuees; this characteristic continues under emergency conditions. The 'cross section' also shows a limited impact, on the total evacuation time, of losing one or more exits (increases of 4.5% in case 1, 17.3% in case 2, and 13.1% in case 3). This might be related to the fact that, in car-based evacuations through small size communities, routing changes imply just moderate extensions in the travelled distance, therefore only a few extra travel minutes (see Table 2).

CASE	NUMBER OF HOUSEHOLDS	AREA (Ha.)	NUMBER OF EXITS	ROAD LENGTH PER HOUSEHOLD (m)	CONDITION	MINIMUM TOTAL EVACUATION TIME (min) / ACCORDING TO MEAN DEPARTURE TIME				
						10 minutes	15 minutes	20 minutes	25 minutes	30 minutes
1	252	74.5	2	20.28	Normal	30.9	41.3	48.9	55.2	57.7
					Emergency (1 exit)	32.3	43.8	50.9	56.6	59.2
2	369	168	3	23.7	Normal	30.1	45.8	50.6	56.3	58.4
					Emergency (2 exits)	35.3	47.5	51.8	58	60.7
3	400	47.3	5	15.38	Normal	32.8	42.8	50.4	55.8	56.7
					Emergency (1 exit)	37.1	47.7	54.5	58.3	59.5

Table 1: expected evacuation times for the three case studies. Source: the authors.

CASE	CONDITION	EVACUATION ROUTES (m)		
		Longest	Shortest	Mean (all routes)
1	Normal	1373.3	52	667.9
	Emergency (1 exit)	1685.8	73.9	1033.5
2	Normal	1411.1	7.1	732.4
	Emergency (2 exits)	2743.8	7.1	1195.4
3	Normal	741	14.9	336.3
	Emergency (1 exit)	1690.7	591.1	1283.4

Table 2: evacuation routes lengths for the three case studies. Source: the authors.

Discussion and limitations

The main finding of this paper is that evacuation appears, based on the modelling, to take considerable time, despite differences in settlement size and pattern in the case studies. Further, in the case of bushfire, the progress of a fire modelled on the 2009 Bendigo Black Saturday event (where a mean rate of spread of 3.2 km/h was measured, according to McCaw et al. (2009)) would overtake the settlements well in advance of people attempting to leave after an evacuation warning. This vulnerability of urban fringe communities to bushfire needs to be accurately grasped by emergency and urban planners.

The results of the model also emphasize that the Victoria's bushfire safety policy 'Prepare, Stay and Defend or Leave Early' policy *is* appropriate for dealing with this type of disaster in these locations. Even for small communities, the activity of departure and travel for all the dwellings is a process that might take a considerable amount of time to be completed, and may increase other risks. In the case

where no safe assembly areas can be provided or the households' fire-resistance capacity is not guaranteed, 'leave early' should be encouraged as the best feasible strategy. As members of communities typically know the fastest or safest way to leave their settlement, an appropriate warning (in terms of accuracy, opportunity, and penetration) seems to be a critical success factor for the whole process. Current efforts in providing massive simultaneous warnings on several media (radio, TV, internet, SMS, etc.) seem adequate, in this respect, at least. The findings of the 2009 Victorian Royal Bushfires Royal Commission (Teague, Mc Leod et al. 2010: 5) reinforce the importance of the 'leave early' approach: "any policy must encourage people to adopt the lowest risk option available to them, which is to leave well before a bushfire arrives in the area".

It has to be underlined that the findings of this paper correspond to small communities in urban fringe areas, i.e. an interface zone between wildland and the city. In comparison to 100% rural areas, this type of location reduces bushfire exposure and facilitates the evacuation process, by providing several exit routes and close safe locations. On the other hand, a community located in a rural area, even with appropriate warning systems and rapid reaction times, may encounter evacuation difficulties due to multiple simultaneous bushfire fronts, fewer escaping alternatives, and longer distances to safe locations.

It is acknowledged that three cases (sharing similar scales) are insufficient to draw wider conclusions and to propose general recommendations about the role of urban structure in bushfire evacuations. However, the preliminary findings are compelling in some ways. In small sized communities, being car-based is a specific factor that mitigates the impact on evacuation time of spatial characteristics such as the distances to travel and the number of exits. However, from the model developed in this paper it can be seen that urban density is a factor that appears to be directly related to expected evacuation times, in a fashion analogous to the occupation rate inside a building. Future models could evaluate the same case studies with a range of densities (e.g. by increasing the number of dwellings) to estimate the rate of this impact, which in turn could lead to the development of urban design standards to improve evacuation in the case of rapid onset disasters, as a new 'safety layer' for these communities. It is also important to include other case studies with larger scales in future studies, eventually whole suburbs with thousands of dwellings. This would assist in better understanding the importance of the actual topological structure of the urban realm, as it would determinate the length of the escaping routes, and therefore the specific time that each dwelling requires to evacuate. The model could also be improved with the incorporation of other parameters, such as various evacuees' behavioural characteristics (e.g. confusion, herding, warning misunderstanding, etc.), re-routing abilities, and environmental real-time features (e.g. fire spread rate, smoke, etc.).

Increasing the understanding about the role of urban structure on emergency response is important in Australia, where little has been done on the road system to manage mass evacuations. Regarding this, some interesting examples are provided by the work of Opper (2004) on flood evacuation planning in New South Wales.

Conclusion

This paper presented a first step in the bushfire evacuation planning analysis of small scale communities in urban fringe areas; they are a common development pattern in current Australia, increasingly located in bushfire-prone territories. As a research method, three case studies in Bendigo, Victoria, were proposed. These were examined with an agent-based model, with an especial emphasis on physical configuration. The results showed that a complete evacuation process may take considerable time, despite the specific size and urban patterns from the communities. When compared to recorded fire spread rates in the site, the involved times demonstrated the vulnerability condition of these communities. The model also confirmed the 'leave early' as an appropriate

emergency policy, and the critical importance of the average departure time in the total required time for evacuating the community, which raises the urgency of timely warning systems, with a high degree of penetration across the population. Future work with the model could be improved with the incorporation of other parameters, such as various evacuees' behavioural characteristics (e.g. confusion, herding, warning misunderstanding, etc.), plus environmental real-time features (e.g. fire spread rate, smoke, etc.). Along with this, other cases could be analysed, using different locations and densities. A more complex and comprehensive model, in turn, might support the proposal of evacuation-based design standards for urban areas, as they already exist in the case of buildings.

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