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Modelling human behaviours in disasters from interviews: application to Melbourne bushfires

Carole Adam¹ * and Benoit Gaudou²

¹ Grenoble Informatics Laboratory (LIG), University Grenoble-Alpes, France
`carole.adam@imag.fr`

² Toulouse Computer Science Institute (IRIT), University of Toulouse, France
`benoit.gaudou@ut-capitole.fr`

Abstract. This paper describes a model for raising the decision-makers' awareness of the real (irrational and subjective) behaviours of the population in crisis situations. We analyse residents' statements and police hearings gathered after Victoria Black Saturday bushfires in 2009 to deduce a model of human behaviour based on the distinction between objective (capabilities, danger) and subjective (confidence, risk aversion) attributes, and on individual motivations. We evaluate it against observed behaviour archetypes and statistics, and show its explicative value.

Keywords: Human behaviour modelling, agent-based social simulation, crisis management

1 Introduction

Natural disasters have been getting more and more frequent recently and cause many victims every year. It is particularly important, in order to decrease the number of victims, to prepare the population and the decision-makers in advance so that they can react appropriately when a crisis occurs. In this paper we are interested in the bushfires in the state of Victoria in Australia. The current policy is "Prepare, stay and defend, or leave early", so the population is given a choice between: evacuating early, before fire reaches their area of residence, because "many people have died trying to leave at the last minute" [4]; or stay and defend their house, only if very well physically and mentally prepared. In both cases, the decision must be made and a plan prepared well in advance. But in the summer 2009, serious bushfires devastated a part of Victoria, culminating on the Black Saturday 7th February when 173 people died, despite all efforts at raising awareness. Several reports [15, 13] have tried to explain the reasons for this heavy death toll and have identified inconsistencies in behaviour (the population does not react as expected by decision-makers), in information (received information is not always considered as relevant by the population), and in communication means (inefficient, specifically information *broadcast*).

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We focus on the discrepancy between the population behaviour as expected by the decision-makers (that determines what information is sent) and their actual behaviour (that determines what information they would need or find relevant). We propose to explain this mismatch by a gap between objective and subjective values of two aspects: risk, and ability to control it. Decision makers tend to predict behaviour based on objective values, while each resident behaves based on their own, necessarily biased, subjective values. Our approach is agent-based modelling and simulation, where autonomous entities (agents) represent the human residents. We have analysed witness statements to design a conceptual model of population behaviour consistent with psychology (Section 2); implemented it on the GAMA simulation platform (Section 3); and evaluated it against behaviour data (Section 4). We conclude (Section 5) with a discussion of these results, comparison with related works, and future directions of research.

2 Conceptual model of population behaviour

Methodology. There are 2 main difficulties in building a realistic agent-based model of human behaviour: finding the right balance between model descriptivity (realistic enough to accurately describe and generate real human behaviour for each agent) and complexity (yet simple enough for its results to be easily understandable) [6, 2]; and finding and exploiting data to inform the model. In this paper we manually analysed several types of data about the 2009 bushfires: 100 witness statements [18], 86 police hearings about circumstances of deaths [17], and statistics about the fatalities [16]. The next section discusses a number of relevant extracts and how we exploited them to design and inform our model.

2.1 Witness statements and statistics

Under-estimation of danger. Reports state that "among those who died, some misinterpreted the information they had received, not realising how little time they had to respond or how soon the fire would reach them". As a result they did not have enough time to implement their fire plans. Even people who did not plan to defend still found themselves forced to when surprised by the fire. For instance, this father:

When we headed up to [the] property, there was just a little fire at the bottom of the hills and I didn't think there were any major dramas. [...] I wasn't too worried at that stage as the smoke was still two valleys away. [...] We watched the fire come up. [...] When I saw them knock the fire off the top of the hill I was quietly confident that we were going to be okay then. [...] As soon as I saw the smoke I decided it would be too dangerous to drive the 5km bush track out. I then prepared to face the fire.

Over-estimation of capabilities. Many residents had over-estimated their ability to face the fires, and were unaware and unprepared.

Although I had never really given it much consideration, I suppose that my fire plan always consisted of staying and defending my property. [...] Nothing

prepared me for this bushfire. Although I never thought about leaving, I now know that my decision to stay and defend was not a well-thought-out decision and that I was very underprepared. In particular, I was psychologically unprepared to fight a bushfire. I simply did not have any idea what the reality of facing a fire would be.

Others did not update their perceived ability with their current condition (age, illness), like this woman's now elderly husband who insisted on defending:

[He] was in Marysville during the 1939 bushfires and fought the fire from the roof of our old house and helped to successfully save that house. [He] also spent many years working for the Forestry Commission and one of his jobs there was to go to different places to fight fires. During his younger years, [he] was a very fit and strong man. [...] During the last few years of his life, [his] health deteriorated, [...] he had a degenerative spinal disease which affected his mobility. [He] was a proud man and [...] he found his loss of mobility very difficult to accept.

Reports confirm that "most of those who died did not, and often could not, respond appropriately to the risk that the bushfires presented for them on 7 February"; in particular 30% of fatalities occurred in undefendable properties.

Passivity. Many people stayed passive in front of fire until it was too late, therefore feeling as if everything went too fast. It was reported [16] that 69% of the fatalities were "passively sheltering" when they died.

This was not a conscious decision, but I was standing just outside the house watching for flames and when they came, they came so suddenly that I just didn't have time to do anything or than stand and watch. It feels almost sacrilegious to say this, but I found the fire fascinating and strangely beautiful. The contrast of the black and red was stunning.

Individual differences. Different individuals can have different perceptions of risk and motivations, resulting in emotions, and a negotiation of the decision.

She was determined to leave, but [her husband] wouldn't leave his parents. [His father] wouldn't go, [his mother] wouldn't leave [his father], [her husband] wouldn't leave his parents.

In that first statement, all four members of the family died in their house. In another statement, the wife ended up escaping alone to safety.

I continued to talk to [my husband] and tried several times to persuade him to leave, but he would not budge. I could smell the fire, I could hear the fire and I could see it with my own eyes. But I couldn't get my husband to accept that it was coming. He just sat and sat and sat. [...] I decided that I could not stand it any longer. I was feeling very anxious and angry with [my husband]. I kept saying "hurry up, come on we've got to go". The fire seemed to be coming closer. I could hear the fire crackling. After too much of that I thought "I'm not staying here to burn". So I walked out the gate and I left the house on foot. [...] I had no idea where I was going the only thing I can remember is that I wanted to get out. I was not thinking clearly because I was so annoyed with [him] and I was also feeling terribly guilty about leaving him. I still have this guilty feeling because I survived and he didn't.

External motivations to defend. People can have additional motivation to defend their house, for instance for financial reasons. Some residents report having stored expensive equipment or personal belongings.

I also had many belongings stored on [the] property in four sheds. I am a hoarder by nature [...]. My belongings included the fit out of a cafe that I used to own, \$50,000 - \$60,000 worth of tools [...]. I also stored family photos and personal papers in the sheds.

Others report drawing additional income from cattle or plantations.

[We] are both retired teachers. The olive grove had been planted in 1999 and the trees were at full production. Both the cattle and the olive grove provided additional income for our retirement.

In both cases they tried to protect their belongings from the fire.

Summary. In conclusion, the manual analysis of these statements highlighted the following factors that we want to include in our model: discrepancy between actual danger and perception of risks; discrepancy between actual abilities and confidence in one's abilities; inter-individual differences in initial motivations for defense (*e.g.* financial) or escape (*e.g.* risk aversion); inter-individual differences in awareness of and knowledge about fires. It also showed that residents go through different stages based on these factors (unaware, passive, preparing, defending, escaping...); can stay in each stage for a varying amount of time, with many residents surprised by the fire while still indecisive or passive (58% of fatalities had made no preparation at all, neither for leaving nor for staying); and can die in any of those stages.

2.2 Behaviour model: finite state machine

In order to highlight the role of these subjective, irrational determinants of the decisions and behaviours of each resident, we need a model descriptive enough to capture these factors, but not so complex that the results will not be understandable. Our choice is to model the population as heterogeneous agents, each having their own values of attributes (individual motivations, subjective risk, subjective abilities, etc), and a finite-state-machine architecture with the following states and transitions (cf Figure 1) inspired by the stages observed above:

- **Unaware:** initial state where the agent is (rightly or wrongly) unaware of any danger, and does nothing; agents can become aware by spotting fires in their perception radius (see flames, smell smoke...), with a probability based on their objective abilities; they update their value of subjective danger based on their perceptions and motivations;
- **Indecisive:** the agent is aware of some fires but has not yet made a decision about how to react; agents stay indecisive for a varying amount of time, until they have enough motivation to either fight or escape; initial motivations are individual and then vary based on the evaluation of the situation (subjective danger);
- **Preparing to escape:** the agent has decided to leave and starts preparing, until ready or surprised by the fire before being ready (transition to **Escaping**), or blocked by the fire and forced to stay (transition to **Preparing to defend**);

- **Escaping:** the agent is evacuating towards the closest shelter; travel efficiency depends on objective abilities; injuries can be received from fires on the way. Unless it dies during travel, its next state will be **Safe** when reaching the shelter;
- **Preparing to defend:** the agent has decided to defend, or was forced to stay because the fire blocks escape; it prepares house and self until the fire is close enough, which triggers the transition to **Defending**;
- **Defending:** the agent is actively fighting the fire around its house; when that fire is extinguished, the agent transitions back to **Preparing to defend** until another fire comes; if motivations change (*e.g.* subjective danger increases when actually seeing the fire, or subjective abilities decrease after failing to fight) and evacuation becomes more urgent, the agent transitions to **Escaping**;
- **Safe:** the agent is (and will stay) in a shelter, and cannot be injured anymore;
- **Dead:** the agent’s health dropped to 0 as a result of injuries received from the fire;
- **Survivor:** final state of all agents that did not die during the fires (*e.g.* successful defenders, lucky passive, and all sheltered residents).

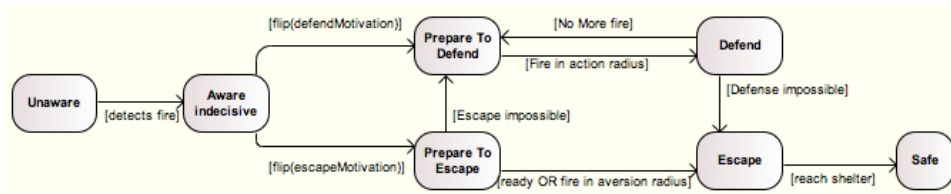


Fig. 1. Residents behaviour: states and transitions. **Dead** and **Survivor** states are not shown to simplify the figure, as they can be reached from any other state. The flip function represents probabilistic transitions.

This simple model is sufficient to capture the discrepancies highlighted by the data. Indeed the objective value of danger influences injuries and damage, and the objective value of capability influences the success of actions. But these objective values are inaccessible to the agents, whose decisions are based on their subjective values of danger and abilities, and on their motivations.

2.3 Evaluation of the conceptual model

Comparison with the psychology of stress. Our model is in agreement with Lazarus’ theory of stress [11], making a distinction between two simultaneous processes: **primary (or demands) appraisal** consisting in evaluating the significance of the situation for the individual (good, stressing, or irrelevant), matches our subjective danger; and **secondary (or resources) appraisal** consisting in evaluating the individual’s capability (skills, social and material support, resources) to cope with the stressor, matches our subjective ability.

Comparison with cognitive bias theories. Behaviours reported in the statements are consistent with known cognitive bias [19, 10], in particular the *confirmation bias*, a tendency to give more credit to information consistent with

one’s beliefs or motivation and to discard inconsistent cues (*e.g.* interpreting the presence of firemen as a sign that everything is safe, or denying the reality of the fire when wanting to stay). Our model allows to capture such a bias, because motivation plays a role in the computation of subjective danger and ability.

3 Implemented model of behaviour in bushfires

3.1 Model of environment

We implemented the model in the GAMA simulation platform [7]. For the sake of simplicity, the environment is a grid containing the different types (houses, shelters, fires, and residents). This simplistic environment is not realistic but is sufficient to simulate the residents’ decision-making in reaction to fires.

Fire. Very complex and detailed models of fire spreading already exist [5], but realistic fire behaviour is not the focus here. Still with the goal of not adding unneeded complexity, we have designed a very simplistic model of fire that is sufficient to trigger and visualise the reactions of the population that we are interested in here. The fire is composed of fire agents (each with a location and an intensity representing its radius of action), having a reflex architecture, *i.e.* the following reflexes are triggered at each step of the simulation:

- **Increase or decrease intensity:** probabilities are parameters.
- **Propagate** to a non-burning neighbour cell, creating a new fire agent. Probability of propagating, and starting intensity of new fires, are parameters.
- **Deal damage** to buildings in its radius of action (based on its intensity): the amount of damage is picked randomly between 0 and a maximum value, function of intensity and a ”damage factor” parameter.
- **Deal injuries** to residents in its radius of action, also random amount between 0 and the maximum value based on its intensity and an ”injury factor” parameter. If the person is in their house, the injury is moderated by its resistance weighed by a ”protection factor” parameter.
- **Disappear** when its intensity is null.

The different parameters involved allow the user of the simulation to make the fire more or less dangerous in order to observe the desired behaviours. Actions are also available to start new fires or stop all fires (and thus the simulation).

Houses. The environment initially contains a number (parameter) of houses each inhabited by exactly 1 resident (in future work we plan to consider families and their relationships). Each house is an agent with the following attributes:

- **Owner:** the resident of that house
- **Resistance:** random initial value between 100 and 200 to simulate different solidity, will be increased by preparing, or decreased by fire damage, and offers some protection from fire injuries to its resident.
- **Damage:** the damage received from fire

The houses collapse from fire damage when their resistance drops to 0. They then cease to offer protection, and the resident’s motivation to defend them also disappears. They stay in the environment as ruins for final visualisation.

Shelters are safe places whose location is known by all residents³. They offer a total protection from fires (no injuries can be received while in a shelter). Once a resident has reached a shelter, they stay inside until the end of the simulation.

3.2 Model of residents

Architecture. We used GAMA finite-state-machine (fsm) architecture for the residents, with the states specified in Section 2: initial state **Unaware**; states during the fires: **Indecisive**, **Preparing to defend**, **Defending**, **Preparing to escape**, **Escaping**, **Dead**, **Safe**; final state **Survivor**, only reached by agents still alive when all fires are stopped.

Attributes. Residents agents have the following attributes and functions:

- **Location** on the grid.
- **House id** (each agent is initially in a house).
- **Current state** (initially unaware, then following the fsm, see Figure 1).
- **Health**: random initial value, increased by preparing for fire, decreased when receiving injuries.
- **Injuries**: total injuries received from fires, influencing decision to escape.
- **Objective defense ability**: random static value impacting the chance to perceive fires in perception radius, and the effect of (prepare, defend) actions.
- **Subjective defense ability**: initialised by applying a (under- or over-estimation) bias (based on confidence parameter and defense motivation) on objective ability, then updated (rate is a parameter) by observing performance (success or failure of defense actions); influences defense motivation.
- **Objective escape ability**: random static value (*e.g.* driving vs walking, fitness), impacting accuracy and speed of evacuation.
- **Objective danger**: based on intensity and distance of all fires around the agent.
- **Subjective danger**: based on intensity and distance of fires known by the agent, moderated by individual motivations.
- **Motivation to escape** (risk-aversion): random initial value, then updated based on subjective danger, health, and resistance of house (offering protection); determines the decision to escape.
- **Motivation to defend**: random initial value (*e.g.* financial reasons, previous experience), then updated based on injuries and damage received, and on subjective evaluation of danger and of fighting abilities.

Actions. Residents agents can perform three actions depending on their state:

- **Prepare**: action performed while in **Prepare to defend** or **Prepare to escape** state; consists in raising resistance of the house (watering, weeding, etc) and health (wearing appropriate clothing, etc), by an increment based on objective ability; success or failure influences subjective ability.

³ In future works we want each resident to have a different (partial, and possibly wrong) knowledge of the position of existing shelters, to simulate varying degrees of preparation, but this adds a lot of computational complexity to the model.

- **Fight fire**: action performed while in **Defense** state to decrease the intensity of nearby fires by a value based on objective ability; agents monitor success to update subjective ability, thus reconsidering their motivation over time;
- **Escape**: action performed while in the **Escaping** state, to head towards the closest shelter, with speed and accuracy based on objective escape ability (could take detours); they might get injured if travelling too close to the fire.

4 Results and evaluation of the model

4.1 Implementation of the simulation

The environment is a 50x50 non-torus grid (cf Figure 2), initially containing 2 shelters in the NE and SW corners (blue-green circles) and 200 houses (grey squares) inhabited by 200 residents. Attributes are randomly initialised (health and resistance between 100 and 200; capabilities and motivations between 0 and 1). The simulation starts with 20 medium fires (orange triangles) that then grow and propagate. Burning cells are in red, surrounded by yellow cells (radiant heat, radius equal to the fire intensity); green cells are safe. At runtime, the user of the simulation can start random new fires or stop all fires, and can specify 3 categories of parameters concerning: fires (probability to grow or propagate, initial intensity, damage factor, etc); buildings (resistance, protection factor, etc); and residents (confidence bias, perception and action radius, etc).

The residents have 2 colours to visualise their current (outside colour) and previous (centre colour) state in the fsm: dark blue (**unaware**), pink (**indecisive**), orange (**preparing to defend**), red (**defending**), yellow (**preparing to escape**), light blue (**escaping**, with an additional nuance of blue grey if escaping before they are ready), dark green (**safe**), black (**dead**). There is no specific colour for the **survivor** state as it is reached by all agents still alive when the fire stops.

4.2 Evaluation methodology

Our model is aimed at the reproduction of realistic human behaviours (and not at realistic initial situation or fire spreading), and should therefore not be evaluated as a whole. This is why we focus here on evaluating the generated human behaviour. We have implemented a tool to track and log the agents' states trajectories: what states they went through, at what cycle, and what were the values of their attributes when making the transition. This allows us to study and explain what happens in the simulation. Thanks to this tool, we can evaluate our model on two axis: **correctness**, by comparing the generated trajectories with those observed in the real population (profiles of behaviours), and in particular comparing the causes of deaths; and **explicative value**, by showing the importance of the subjective-objective discrepancy, thus proving the potential of our model to raise decision-makers' awareness of this gap.

4.3 Evaluation of the correctness of model

Consistency with behaviour profiles. A report [1] has established 6 profiles of behaviours in the residents of fire-affected areas: **can-do defenders** (most

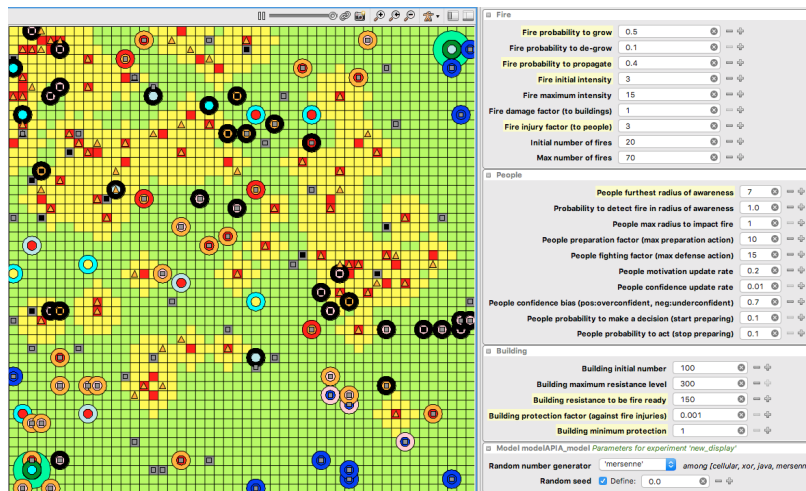


Fig. 2. Screenshot of the simulation in GAMA, with parameters and their values

determined, experienced, self-confident and skilled, determined to defend); **considered defenders** (strongly committed to defend, aware of risks, well prepared and trained); **livelihood defenders** (committed to defend their livelihood, well prepared); **threat monitors** (not intending to stay in front of a serious threat, nor to leave until necessary, wait and see); **threat avoiders** (aware of risks and vulnerability, plan to leave early before any real threat); **unaware reactors** (unaware of risk, feel unconcerned, no knowledge, preparation or training).

We were able to observe the same profiles of behaviours in our simulation, and to categorise the agents in these profiles based on their logged trajectories. For instance a typical trajectory for a can-do defender is an early perception of the fire (transition to **Indecisive** followed by an immediate decision (transition to **Preparing to defend**), an efficient preparation (strong improvement of health and resistance in that state) and defense (big decrease of fire intensity). Also they have a good perception of risks and are able to reconsider their intention (transition to **Escaping** when health decreases too much), unlike livelihood defenders who tend to stay on their property no matter what happens. We have then computed average values of the attributes in each category of agents and compared them with the global value on all agents. For instance we found that can-do defenders have a significantly higher self-confidence, which is in agreement with the definition of the profile.

Consistency with death causes statistics. The VBRC report also provides statistics about the circumstances of the 173 deaths drawn from police hearings and experts reports. In particular they found that 14% died while fleeing (4% in cars, 10% on foot); 69% while "passively sheltering" (as opposed to "actively defending"), possibly after having tried to defend; some died while defending, even when well prepared. In total 30% were taken by surprise by the fire. Figure 3 (left) shows the percentage of deaths from each state in our simulation. With a first manual calibration of our parameters, we obtained a distribution of behaviour relatively similar to the real population: 47% of the agents died while

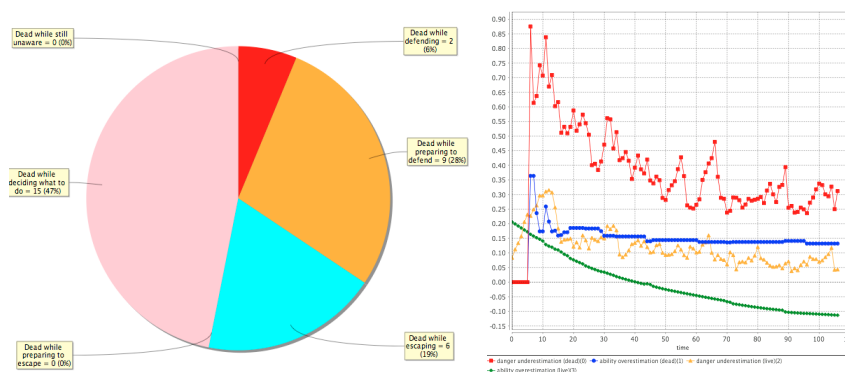


Fig. 3. (left) Causes of death in our simulation. (right) Average discrepancy between objective/subjective perception of danger and abilities in alive/dead agents.

still passive (indecisive); 19% die while escaping; the others died while preparing to defend or defending, taken by surprise before they could evacuate. In future works we will do a sensitivity analysis to reduce the number of parameters, and do an automatic calibration of our model.

4.4 Explicative value of our model

The goal of our model is to raise decision-makers' awareness of the factors determining real population behaviour, as opposed to expected behaviour. Indeed, the statements clearly show that decision-makers expect a "rational" behaviour based on objective values, while people behaved based on their subjective (possibly wrong) values. Our hypothesis was that the discrepancy between these objective and subjective values of danger and capabilities could explain deaths, and should therefore be taken into account. If we are right, we should observe stronger discrepancy in agents who die than in agents who survive.

Figure 3 (right) shows the evolution over time of the average discrepancy between objective and subjective values of danger and capabilities, for alive agents and for dead agents. Note that once dead, agents do not update their values, so the evolution only comes from new agents dying over time.

- **Danger discrepancy for dead agents** (red) starts at 0 (no death yet) then jumps to a very high value as the first agents die while unaware of (yet real) danger. It then tends to decrease as the agents dying later in the simulation are those who have a lower underestimation of danger.
- **Danger discrepancy for alive agents** (orange) is always much lower than in dead agents; it also continuously decreases for two reasons: agents with a higher discrepancy die, and those that survive update their perception of danger to tend towards the objective value.
- **Ability discrepancy for dead agents** (blue) also starts (and stays) higher than for alive agents. It decreases quickly at the start (as agents with higher discrepancy died early), then stays mostly stable.

- **Ability discrepancy in alive agents** (green) keeps going down, until the last survivors tend to actually underestimate their abilities (this is due to them updating their subjective abilities based on their performance at fighting the fire, which gets worse as the fire keeps intensifying).

5 Discussion and conclusion

Summary. In this paper we therefore provided a realistic model of population behaviour, based on qualitative data from interviews, consistent with statistics of causes of deaths, and with a high explicative value. This model can therefore be used to predict behaviour, in order to raise awareness of decision-makers, and also to let them explore various strategies for reducing population vulnerability.

Comparison with state of the art. Some existing simulations focus on realistic fire behaviour and spreading (*e.g.* Phoenix [5]), easier to understand in physical terms. On the contrary as far as we know no model provide the same degree of realism for human behaviour. Indeed, many agent-based simulations focus on crowd evacuation in building fires, with often homogeneous reactive agents (*e.g.* social force model [8]). More complex models have then appeared, integrating emotions [12, 14] or social relationships [3] of agents, but they are usually based on psychological theories, while we based our model on witness statements providing a precise description of people actual behaviour.

Existing simulations often focus on the evacuation of public buildings (*e.g.* airport [9], stadium) to inform their design and prevent problems (*e.g.* crowding at doors or in stairs) which are not relevant in bushfires in scarcely populated areas. Besides, most of these simulations tend to focus on evacuation itself, neglecting the pre-evacuation time which is at least as important [10]. On the contrary we did model this decision-making phase, which is even more important in bushfires where people are not evacuating from a public building (where their only motivation is to save their life) but have to abandon their own house to the flames (with an additional contradictory motivation to also save it).

Future work. Our model relies on simplifying hypotheses and will need to be extended in the future. In particular, the initial situation has exactly one person per house, while statements and reports show the importance of family relationships (several people in the same house making a decision together), and of tourists or visitors who (in addition to their lack of knowledge) have nowhere to go when the fire surprises them outside. Also, we need to model how different sources of information (observation of fire, information on the radio, visits from authorities, phone calls from relatives, etc) with different levels of trustworthiness are combined to evaluate risk and make a decision.

Our agent architecture is also very simple, tailored to prove our point about the discrepancy between objective and subjective values of danger and ability. In future work we plan to design a BDI (belief, desire, intention) model of behaviour, improving its descriptivity but also its explaining power, since mental

attitudes are people's preferred level of abstraction to explain behaviour [2]. Thanks to this high explicative value, we aim to eventually transform this simulation into a serious game which will be a valuable tool for decision-makers to test response strategies or raise the population's awareness.

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