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Examining the potential of mobile applications to assist people to escape wildfires in real-time

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ABSTRACT

Over the past couple of decades, the number of wildfires and area of land burned around the world has been steadily increasing, partly due to climatic changes and global warming. Therefore, there is a high probability that more people will be exposed to and endangered by forest fires. Hence there is an urgent need to design pervasive systems that effectively assist people and guide them to safety during wildfires. This paper examines the potential of mobile applications to be employed to assist people to escape wildfires in real-time, by means of using and evaluating EscapeWildFire, a system for suggesting evacuation paths to mobile phone users in real-time. Two different evaluation strategies are followed: (a) Considering different areas of the island of Cyprus as case studies with simulated wildfires and actual users and (b) Considering a historic wildfire that occurred in Amarillo, Texas in 2011. Results in both cases show that mobile apps can effectively be employed to assist people to escape wildfires, but their use is heavily dependent on a backend system that supports the precise modelling of the wildfire. The time between the wildfire outbreak and the notification reaching the user is crucial for their safety. Various recommendations for improvements have been recorded based on either the feedback of participants in the case studies or the observations from the Texas wildfire. The code of the mobile app, backend and administration interface used are all open-source; fire authorities around the world are encouraged to further investigate this opportunity and adopt this approach.

1. Introduction

Over the past couple of decades the number of wildfires and area of land burned has been steadily increasing [1,2], partly due to climatic changes and global warming [3,4] and partly due to increased urbanization next to vegetated areas and poor land management [5]. A wildfire is defined as a large, destructive fire that spreads quickly over woodland or bushes. It differs from fires that occur in urban infrastructures and buildings [6–10]. USA and Australia have suffered significantly during recent years, experiencing some of the worst wildfires in decades. Every year approximately half a million hectares of land are burned by wildfires in southern Europe [2]. Moreover, the frequency of these fires is projected to increase by 27% in the coming decade [11,12].

Since the Indian Ocean tsunami of December 2004, there has been a surge of interest in developing early warning systems to aid countries in disaster management [13]. However, recent history has shown that

many countries are not well-prepared for natural disasters such as wildfires [14,15]. The recent examples of Australia, Portugal, Norway and Greece are quite alarming, especially since human casualties have been reported [14,16]. In Canada, few First Nations have an up to date emergency plan tailored to their community [15]. There is a high chance that more people will be endangered by wildfires in the coming years and this will likely be associated with further casualties [12].

Countries tend to deal with increasing wildfire hazards by improving their equipment and capacity in human resources: better observations, helicopters and UAVs, as well as new fire-retardant chemicals [13,17–21]. However, the infrastructures of most countries are lacking in the evacuation of humans from the fire zones, despite evacuation plans being in place. Furthermore, the evacuation plans in regions where forest fires are not common (e.g. northern Europe such as Netherlands and Nordic countries) have not been fully implemented or tested for safety [22].

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The factors associated with human casualties include delayed dissemination of warnings (i.e. warning time) and delays in implementation of evacuation advice (i.e. response time) [23]. Thus, people leaving too late is not only about poor warning, but it is also linked to people taking the decision too late, even after having received the warning. As a result, evacuees leave areas at risk with only minutes to spare, encountering dangerous conditions in the process [22]. One of the critical aspects in WUI wildfires is often the response time (i.e., the time to decide to evacuate), along with the time to get the evacuation order. People may also decide to stay anyway, to defend their properties [24]. Strahan et al. observed and proposed seven archetypes that characterize the diverse attitudes and behaviour of typical groupings of householders faced with making a protective decision during a bushfire [25].

This paper aims to propose more informed and intelligent evacuation plans in cases of wildfires occurring at the wildland–urban interface (WUI), which is a zone of transition between wilderness and land developed by human activity, an area where a built environment meets with a natural environment. Human settlements in the WUI zones are at a greater risk of catastrophic wildfires. In the work of Modugno et al. [26], European WUI areas have been correlated with occurrence of large burned surfaces. The contribution of this paper is to help tackle the unpreparedness of many countries and regions around the world for wildfire evacuation [22], by considering the potential of employing emerging technologies such as mobile phone apps, earth mapping and location-based services, in order to assist people to safely evacuate wildfires in real-time. In contrast to related work, which focuses on large-scale evacuations of the population (e.g. [27,28]), our work focuses on how individuals who are exposed to the wildfire may safely evacuate, based on their precise location and evacuation options available, considering various transportation modes, including on foot and by bike. The proposed solution respects people’s privacy.

To better assess the use of these technologies, the *EscapeWildFire* system is employed [29], which is a system designed and implemented to assist citizens to escape wildfires by offering evacuation routes to them. The *EscapeWildFire* system involves a mobile application, a backend and an administrative interface. This system has been created as open-source code,³ together with complete user manuals and instructions.

This paper examines the potential of the use of mobile apps and such systems to assist people to safely escape life-threatening wildfire situations, mainly those occurring in WUI zones, via the following aspects:

1. Description of the system requirements, defined based on a state-of-the-art literature review as well as the guidelines provided by officers of the Fire Authority of Cyprus, who participated in this project as partners;
2. A complete design of the proposed system and an ideation on how the evacuation process should work;
3. An evaluation of the system by simulating wildfires in various landscapes (i.e. natural reserve, rural-area village, suburban area) with actual users and different transport modes (on foot, bike and car);
4. An evaluation of the system by studying a historic wildfire in Amarillo, Texas in 2011;
5. An elaborate discussion including limitations, recommendations and future work.

The rest of the paper is organized as follows: Section 2 presents related work while Section 3 lists the requirements and introduces the ideation and proposed design of such a system. After, Section 4

explains the implementation efforts for the development of the *EscapeWildFire* system while Section 5 describes our evaluation efforts to assess the proposed approach, presenting the evaluation results. Finally, Section 6 discusses the overall implications of the proposed approach and Section 7 concludes the paper.

2. Related work

Much work has been performed on fire evacuation and a wide plethora of solutions have been proposed in regards to different protocols, escape routes, time required to evacuate, human behavioural patterns during fires, congestion avoidance, etc. Some papers forecast and visualize the wildfire in geo-visualizations [21]. Verification and validation of various evacuation models are discussed in [30].

Most of the work has focused on evacuation from houses and buildings [6,31], however some evacuation models were proposed or applied to assess and analyse the safety of various infrastructures such as road tunnels, high-speed trains and hospitals [7–10]. Mostly urban areas were considered for evacuation, some authors considering neighbourhoods [32,33] and streets (i.e. pedestrians, traffic) [30,33].

Regarding wildfires in particular, related scientific work targeting real-time evacuation assistance is very limited [22]. Evacuation models require data on decisions and behaviours during evacuation movement, including which routes evacuees will take to reach safety, what destinations will be used as safe locations, and many other evacuation movement concepts [22,34]. Human behavioural patterns during fires are important to be modelled and understood, for evacuation models to work. Strahan et al. recognized seven archetypes that characterize the attitudes and behaviour of householders when deciding their actions during bushfires [25]. Singh et al. applied those self-evacuation archetypes to an agent-based model of community evacuation in regional Victoria [35], to achieve more realistic bushfire evacuation modelling. Adam and Gaudou [31] proposed a model for predicting how people behave when evacuating their homes, based on the observations and testimonies of citizens during the Melbourne bushfires.

Targeting evacuations from WUI zones, Beloglazov et al. combined evacuation modelling and simulation systems [27], arguing that the behaviour of people is a key factor during a wildfire evacuation. An approach was proposed that combined several simulation and modelling systems, including a wildfire simulator, behaviour modeller, and microscopic traffic simulator. Similarly, the WUI-NITY platform [28] aspired to enhance the situational awareness of responders and residents during evacuation scenarios by providing information on the dynamic evolution of the emergency (i.e. predictions of evacuee performance), based on simulations performed via a gaming engine.

WFA Pocket [36] is a tool targeted for firefighters, designed to be used in the field, modelling the progression of the fire based on the user inputs, such as the fuel types, real-time weather data, etc. WiSE,⁴ which is a business initiative tool designed to provide safe separation distance (SSD) calculations to wildland firefighters. This tool enables firefighters to identify suitable safety zones while in the field. Calculations based on user inputs from direct observations allow the firefighters to effectively manage the fire whilst maintaining safety. Input parameters that can be entered by the user include: wind, slope, fuel height and resource information. Using these inputs, the individual can quickly calculate their SSD and view the results on a map [37].

Gaia GPS⁵ is a mobile app that has been used by firefighters to plan escape routes, mark fire lines, and track progression. In the latest version, users are also able to create polygons on the map and measure the area and perimeter of fires. Disaster Alert [38] is another mobile

³ *EscapeWildFire* software. <https://github.com/superworld-cyens/Escape-Wildfires>.

⁴ Wildfire Safety Evaluator, <https://wise.wildfireanalyst.com>.

⁵ Gaia GPS, <https://www.gaiagps.com>.

app based on PDC's DisasterAWARE platform⁶ that provides the user with near real-time information about 18 different types of active hazards. This includes, but is not limited to, hurricanes, earthquakes, volcanoes and wildfires.

The FEMA app⁷ is available in US and provides the user with real-time alerts from the national weather service for up to five locations, allows the user to share real-time notifications and locate open emergency shelters and disaster recovery centres. It also contains some safety tips, emergency check-lists, family plans and reminders; enabling the user to register for disaster assistance online. Similarly, the Hazards app⁸ has been developed by the Global Disaster Preparedness Center and is mostly concerned with informing the user of and preparing the user for potential danger. It offers an alert system that can deliver official watches and warnings from alerting agencies.

Finally, Emergency is an application developed by the American Red Cross [39], with the aim to keep people safe in severe weather conditions as well as man-made or natural disasters. This is achieved by monitoring conditions in at the users' locations; preparing their families and homes for up-coming disasters; and checking to see if their loved ones are safe. The disasters addressed by the app include, but are not limited to: severe weather, tsunamis and wildfires.

Summing up, the aforementioned works either focus on other types of fires and settings (e.g. buildings, neighbourhoods and infrastructures) [6–9,22,32–34], or on the informational aspects of wildfires (FEMA, Hazards, Emergency), firefighters' support (WiSE, Gaia GPS) or citizens evacuating their homes [31]. The evacuation plans and proposals of related work mainly focus on urban settlements, not dealing with WUI areas. The only papers actually dealing with WUI zones is the works of Beloglazov et al. [27] and the WUI-NITY platform [28], but the aim there is to predict the outcome of various wildfire evacuation scenarios, targeting authorities, experts, operators (e.g. emergency service personnel) and policy-makers, and not the actual, real-time support of civilians via location-based services from mobile phone apps, which is the goal of this paper.

3. Requirements and design

This section discusses the requirements and design decisions for a correct and acceptable system that assists people to effectively escape wildfires via mobile phone applications.

3.1. Requirements

Requirements focus mostly on features of the mobile app, which have been defined based on a state-of-the-art literature review (see Section 2), as well as guidelines provided by officers of the Fire Authority of Cyprus, who participated as partners in the Cyprus case study (see Section 5.1). Since the scenario is about wildfires and (mostly) rural areas, people are expected to evacuate the area instead of trying to protect it, as they are most likely far away from their homes (i.e. a choice to evacuate or stay and defend does not apply here) [31].

The main must- and should-have requirements are the following:

- *Wildfire modelling*: The system must take fire progression into account and predict its propagation as accurately as possible.
- *User context*: The user should be able to declare the current transportation method: on foot, by car or by bike. This will allow to provide more contextually appropriate escape routes, with more robust time dependent calculations. The system should consider and provide support for users with disabilities.

- *Escape routes and route calculation*: The system must consider the time between the fire and the evacuee. Maps focusing on navigational assistance are typically better for people with map reading familiarity, while maps focusing on directing users to a destination are generally better for people with a bad sense of direction. Both options should be provided to the users. Polygons should be visible on the map and indicate the fire's progression, this should be shown alongside the escape route suggestions.
- *Real-time information*: Up to date information about the fire's progression, direction and propagation through time should be provided at all times.
- *Simple and flat menu structure*: As the users will be in a high pressure situation, the mobile app interactions should be clear and simple. Users will not have time to navigate through complex menus with multiple considerations.
- *User accessibility*: High visibility should be inherent in the mobile app design. Contrasting colours will be used and option to increase font size included. To avoid confusion, text is generally preferred over icons. A fat-finger interface (big buttons) will be implemented.
- *Enriched map*: The map should be clearly identifiable with the users' surroundings. The inclusion of different layers (shelters, lakes, infrastructures etc.) will aid this. The decision to evacuate or go to the nearest shelter is a topic of active research [23,40,41]. It seems that relative shelter location to ignition strongly affects the efficacy of shelters while the efficacy of shelters depends on the fire's progression [41].
- *Sensing of the current user location*: This is key to effective evacuation and minimization of user confusion. GPS and location services should be accessed in real-time. User location will be continuously compared to the suggested escape route(s), to avoid hazardous mistakes.
- *Multiple modes of transportation*: Evacuees, especially when in rural and/or mountainous areas might decide to switch transportation modes depending on the situation. The mobile app should allow them to choose alternate modes along the way (e.g. considering public transportation options).
- *Propose alternatives*: The system should propose several (alternative) routes for evacuation, in case some routes become unavailable at some point.
- *Escape route context*: The system should consider the slope of the road, the wind speed and direction as well as the age of the evacuee, especially when the evacuee is on foot or by bike. The current traffic conditions and the terrain of the road should be considered when the evacuee is using a car or a bus.

3.2. Mobile app design

The principle idea behind the design is to keep the on-screen information to a minimum. A minimalist design approach with strictly necessary information for the users should be adopted (see Figs. 1 and 2).

At the beginning, the user should only specify mode of transport and preferred map view, as shown in Fig. 1. The fire location and progression indicator are visually encoded with red colour, with dark red at the centre of the fire and increasing transparency further from the centre, indicating time periods of fire progression (Fig. 2, left). Each polygon of increasing transparency indicates the expected propagation of the wildfire after certain duration, depending on the capacity of the system to precisely model and predict the fire's propagation with high confidence. For example, in Fig. 2 (left), there are five layers of the wildfire, at intervals of x minutes after ignition, where x can be 15, 30, 45 min or longer periods. As an example, for the historic wildfire of Amarillo, Texas [42], 30-minute intervals were considered by the local authorities to model and describe the fire's progression.

⁶ Pacific Disaster Center, PDC DisasterAWARE, <https://www.pdc.org/apps/disasteraware/>.

⁷ FEMA, <https://www.fema.gov/mobile-app>.

⁸ Global Disaster Preparedness Center, Hazards, <https://preparecenter.org/activity/universal-app-program/hazard-app/>.

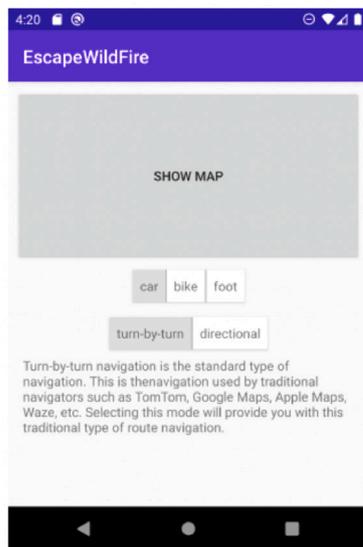


Fig. 1. A snapshot of the welcome screen of the mobile app.

Two different navigational methods can be considered as popular and well-understood by mobile phone users: a *turn-by-turn* view (similar to that used in Google Maps) and a *direction-based* view (similar to compass navigation).

For the turn-by-turn view, (Fig. 2, centre), the top-right corner may indicate the next turn and the turn immediately after, along with the distance until action. At the bottom of the screen, the user has the option to open a complete list of directions. This is a scroll-enabled list, listing turn types alongside the distance to each turn. Next to the direction list is another button to pause navigation, returning to a general overview of the route. Above these buttons, two zoom buttons are placed, offering the option for fine zoom control. For the direction-based view, an arrow inside a white circle (Fig. 2, right) continuously shows the indicated direction of the user, based on current location and orientation.

3.3. Escape routes algorithm

The accuracy of the algorithm used for calculating escape routes is essential for the system's good performance. Each possible route gets a score, depending on the time needed to reach *safety*. Safety is defined as the time needed for a wildfire to reach a user, and it could be elaborated as follows:

- **Safety and no risk:** The user has reached a location where the wildfire is not expected to reach, based on the wildfire propagation model used.
- **High risk:** The user has reached a location where the wildfire is expected to reach in more than x minutes, based on the wildfire propagation model used. In this case, the user is highly recommended to seek alternative transport after this point. The time duration x should be defined by each fire authority and its current policies/operations.
- **No safety and extremely high risk:** The system cannot propose escape routes that lead to safety or at least to high-risk locations. All escape routes give values for the safety time as less than x , or even negative values. In this case, shelters or nearby spots that offer some physical protection (e.g. lakes, water bodies, valleys among high hills) may be considered.

Employing an earth mapping service (e.g. Google Maps, OpenStreet Maps, ESRI ArcGIS, Bing Maps), all possible escape routes are evaluated, considering the user's mode of transport (i.e. car, bike, on foot),

Table 1
Values for user's expected evacuation speed.

Transport type	Speed (km/h)	Penalty for older people
Walking	4.5	40%
Cycling	15	20%
Driving car	50	0%

landscape (i.e. slope) as well as weather conditions (i.e. mainly wind). The route that leads to safety in minimum travel time is considered first. If no routes lead to safety, then the route that offers the lower risk (i.e. wildfire is expected to reach in maximum time) is considered. Future implementations could consider routes with higher risk but closer to public transport, but this needs to be properly organized and coordinated by the local fire authorities and public transport providers, who need to provide emergency evacuations plans.

The pseudo-code of the algorithm is given below:

```

Create candidate routes  $i$  from the user's current location
Create an empty list as time needed to reach end of route  $R$ 
Create an empty list as wildfire progress  $W$ 
Create an empty list as time to safety  $T$ 
Create a list with all the shelters  $S$ 
Get the user's type of transport and age

FOR all candidate routes  $i$  in  $H$ 

    Get the slope and wind at the candidate route  $i$ 
    IF the type of transport is a car
        THEN calculate the possible car route  $R(i)$ 
    ELSE IF the type of transport is a bike or on foot
        THEN calculate the possible route  $R(i)$ 
        IF the user is older than AGE
            THEN add extra time needed to evacuate to the route  $R(i)$ 
        IF the escape route  $i$  has a slope and the user is on bike or on foot
            THEN add extra time needed to evacuate to the route  $R(i)$ 
        IF the route has wind and the user is on bike
            THEN add extra time needed to evacuate to the route  $R(i)$ 

    Calculate  $W(i)$  as time until wildfire reaches end of route  $i$ 
    Calculate time to safety  $T(i)$  as  $R(i) - W(i)$ 
END FOR LOOP

IF some candidate routes  $T$  lead to safety
    RETURN the candidate route  $i$  where  $R(i)$  is the minimum
IF some candidate routes  $R$  lead to high risk
    RETURN the candidate route  $i$  where  $T(i)$  is the maximum
IF no candidate route leads to safety
    THEN RETURN the most close-by shelter
IF no shelters are found
    THEN RETURN the candidate route  $i$  where  $T(i)$  is the maximum
  
```

Routes that pass through wildfire progression zones (see Fig. 2, left) during the user's evacuation, even if the route leads to safety, are rejected immediately. Travel calculations based on type of transport are considered based on the values in Table 1, assuming conservative values for user travel speed. More personalized values depending on someone's fitness or vehicle is an aspect of future work. People above the age of 50 are assumed as older people who need more time to evacuate, but the number 50 is rather arbitrary and requires more investigation. Our preliminary results suggest that people above 50 need 40% more time to evacuate while walking and 20% more time to evacuate while cycling (see Section 5.1).

Wind also influences the speed of a person that cycles. For each wind direction, there is an influence on the user's riding speed. According to [43], the speed of a cyclist is affected up to 20% (negatively) with a head-wind and up to 15% (positively) with tail-wind. With pedestrians, there is not a big noticeable change in walking speed.

Finally, slope affects both people on foot and cyclists. In a study by Castano [44], it was observed that subjects walked slowest during incline walking (0.92 ± 0.18 m/s), faster on a declined slope (1.06 ± 0.14 m/s), and the fastest at level ground (1.15 ± 0.17 m/s). For cyclists, it is a bit different, according to Felix [45], who derived various equations for the speed of cyclists on roads with different percentages of inclination, where the slope heavily affects the performance in speed.

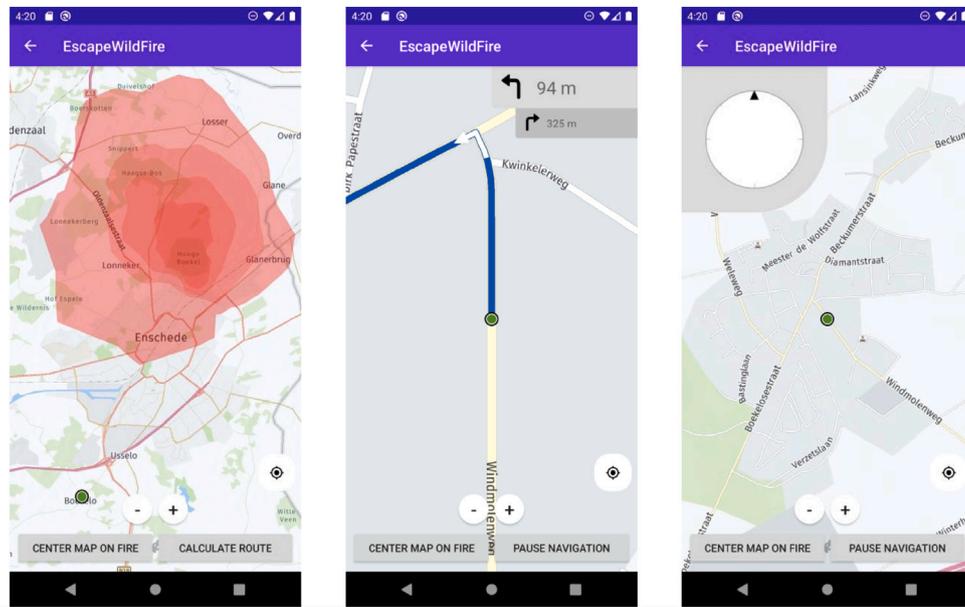


Fig. 2. Snapshots of the mobile app: Fire illustration (left), turn-by-turn view (centre), direction-based view (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

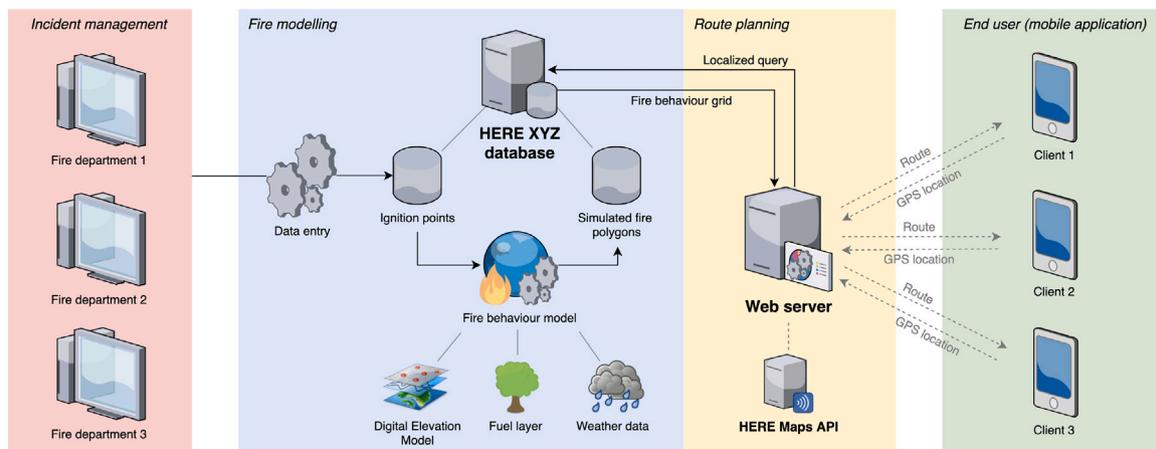


Fig. 3. Architecture of the EscapeWildFire system.

4. Implementation

Based on the requirements and design decisions discussed in Section 3, the EscapeWildFire system’s implementation is presented in the following subsections. Besides the mobile app, a backend system must be in place to support the management of vital information, such as where/when the fire started, how fast it will propagate based on vegetation (fuel) type, wind speed and direction, weather conditions, etc. The architecture of the system (mobile app, backend and administration/management tool) is provided in Fig. 3. The system is composed of the following components:

- Mobile application (see Sections 3.1, 3.2 and 4.1)
- Fire propagation model (FPM, see Section 4.2)
- Web server (HERE Maps API and XYZ database, see Section 4.3)
- Fire administration/management tool (see Section 4.4)

Each fire department has its own version of the fire management tool, which allows them to add ignition points in areas of their responsibility. The FPM analyzes the area around the ignition points

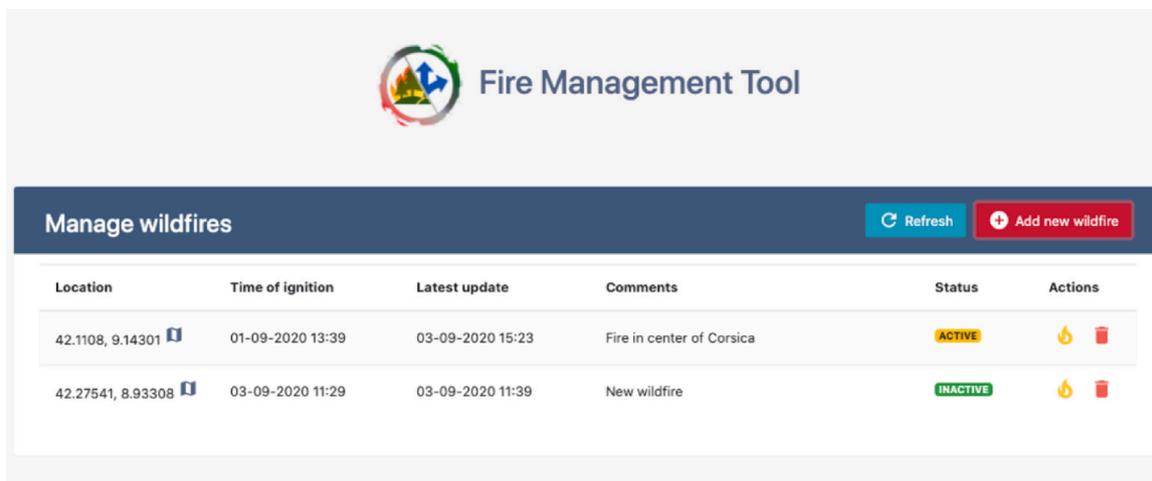
and calculates the fire propagation. The Web server communicates the information from the FPM to the mobile apps of the end users and data is presented in the form of polygons, indicating the spread of the wildfire in x -minute intervals. The mobile apps calculate safe escape routes for the users for effective evacuation. Each paragraph below describes implementation details of the individual components of the system.

4.1. Mobile application

Implemented in Android, based on the requirements defined in Section 3.1 and the design decisions listed in Section 3.2. The map provider is HERE maps,⁹ selected for better interaction with the Web server (see Section 4.3). The app has been listed on Google Play,¹⁰ to

⁹ HERE Maps. <https://mobile.here.com/?x=ep>.

¹⁰ EscapeWildfire mobile app. <https://play.google.com/store/apps/details?id=com.ewf.escapewildfire>.



Location	Time of ignition	Latest update	Comments	Status	Actions
42.1108, 9.14301	01-09-2020 13:39	03-09-2020 15:23	Fire in center of Corsica	ACTIVE	 
42.27541, 8.93308	03-09-2020 11:29	03-09-2020 11:39	New wildfire	INACTIVE	 

Fig. 4. Snapshot of the fire management tool.

facilitate the evaluation process (i.e., for the participants of the case study in Cyprus, to easily download the app, see Section 5.1).

4.2. Fire propagation model

Wildland fire spread simulations are performed by the numerical solver ForeFire [46]. ForeFire relies on a front-tracking method where the fire front is represented by Lagrangian markers that are linked to each other via a dynamic mesh. While the tool can theoretically use any formulations, currently the velocity of every point of the front is provided by the model of Rothermel [47]. The rate of spread (ROS) is expressed as a function of several environmental properties such as wind speed, terrain slope, fuel moisture content and other fuel parameters characterizing the vegetation.

A simulation mostly consists of the definition of an initial state of the fire front and then the ROS is computed for the markers of the fire front based on underlying 2D fields from which environmental properties are determined. ForeFire relies on a discrete-event approach where most computations deal with the determination of the time at which the markers will reach their next destination. Destination here is defined by a fixed spatial increment in the direction at the tangent to the perimeter of the burned area. This discrete-event approach includes other types of events such as changes in the values of the layers, notably wind speed and fuel moisture; additions and removals of markers so that the fire front maintains a perimeter resolution in a given range during the simulation; and topology checks that may induce front merging to ensure that the front keeps a physical representation. Real-time wind information is provided by the Windy¹¹ online service.

The land type distribution field comes from CORINE Land Cover data [48]. The elevation field is extracted from the NASA SRTM dataset,¹² which originally has a 30 m resolution. Fuel parameterization is performed to assign reference fuel parameters to each type of vegetation in the land use data for the ROS computations. Data used for simulation also include 2D fields of wind speed vectors, computed to account for the influence of the elevation field. All these fields are compiled on NetCdf landscape files that are pre-formatted for many latitude/longitude points, providing coverage for Cyprus, the south of France and Corsica, with plans to extend to other European regions. ForeFire simulation is set up as a RESTful service on the server hosting the landscape, with output forecasted fronts generated as JSON data.

¹¹ Windy. <https://www.windy.com>.

¹² NASA SRTM. <https://www.earthdata.nasa.gov/news/nasa-shuttle-radar-topography-mission-srtm-version-3-0-global-1-arc-second-data-released-over-asia-and-australia>.

4.3. Web server

The Web server is responsible for linking the mobile apps of the end users with the backend. The Web server uses the HERE HYZ database and its Maps API in order to properly model fire propagation as polygons, in a language understood by the map provider software used by the mobile app. HERE HYZ.¹³ is a location data management cloud service, built around standards like GeoJSON. It stores data in multiple levels. The top level is called a *space*. Each space is being used to describe one fire, modelled as GeoJSON geometry objects. These are objects like polygons, multi-polygons or line strings. When accessing the service through HERE Maps API, communication is primarily through GeoJSON files.

4.4. Fire management tool

This software is intended to be used by fire departments to manage wildfire incidences, i.e. add/remove, ignite/stop and configure wildfires in real-time. New fires can be added via the “Add new wildfire” button, shown in Fig. 4. When the fire officer clicks this button, relevant details can be added (Fig. 5) such as the exact location where the wildfire started, time of ignition and other important information to be shared with stakeholders (i.e. firefighters and citizens).

5. Evaluation

To assess the proposed system’s performance, in terms of correctness, acceptance and overall potential, two different evaluation options were considered: (a) Different landscapes of the island of Cyprus as case studies with simulated wildfires and actual users; and (b) a historic wildfire that occurred in Amarillo, Texas in 2011. Both evaluation efforts are described below.

5.1. Simulated wildfires at the island of Cyprus

Three scenarios of wildfires were simulated, selecting three different landscape types: a natural reserve (Fig. 6), a linear cyclists’ park (Fig. 7) and a village in the mountains (Fig. 8). These landscapes are located in the region of Nicosia, Cyprus, illustrated in Figs. 6–8, as visualized by the ForeFire fire behaviour modeller [46] (see Section 4.2). The motivation for choosing those scenarios and areas was the fact that they represented completely different landscapes with people passing by in different transportation modes.

¹³ HERE Studio. <https://developer.here.com/products/platform/studio>.

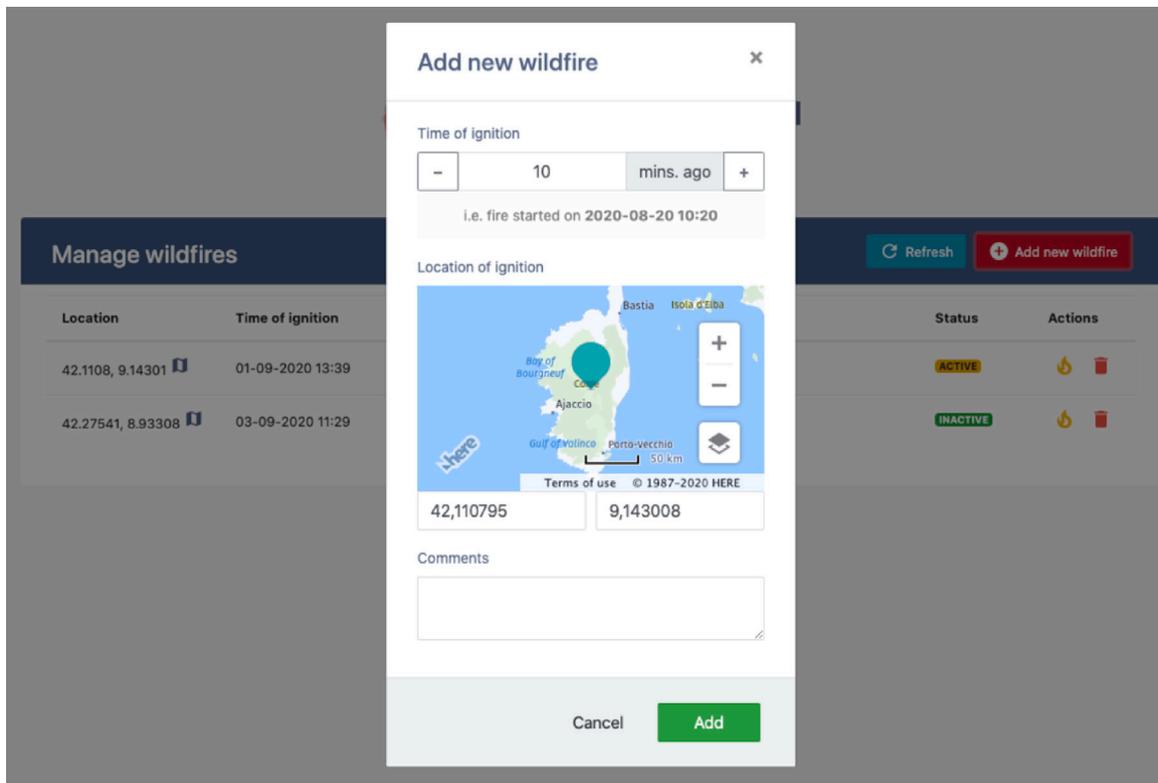


Fig. 5. Snapshot of the fire management tool.

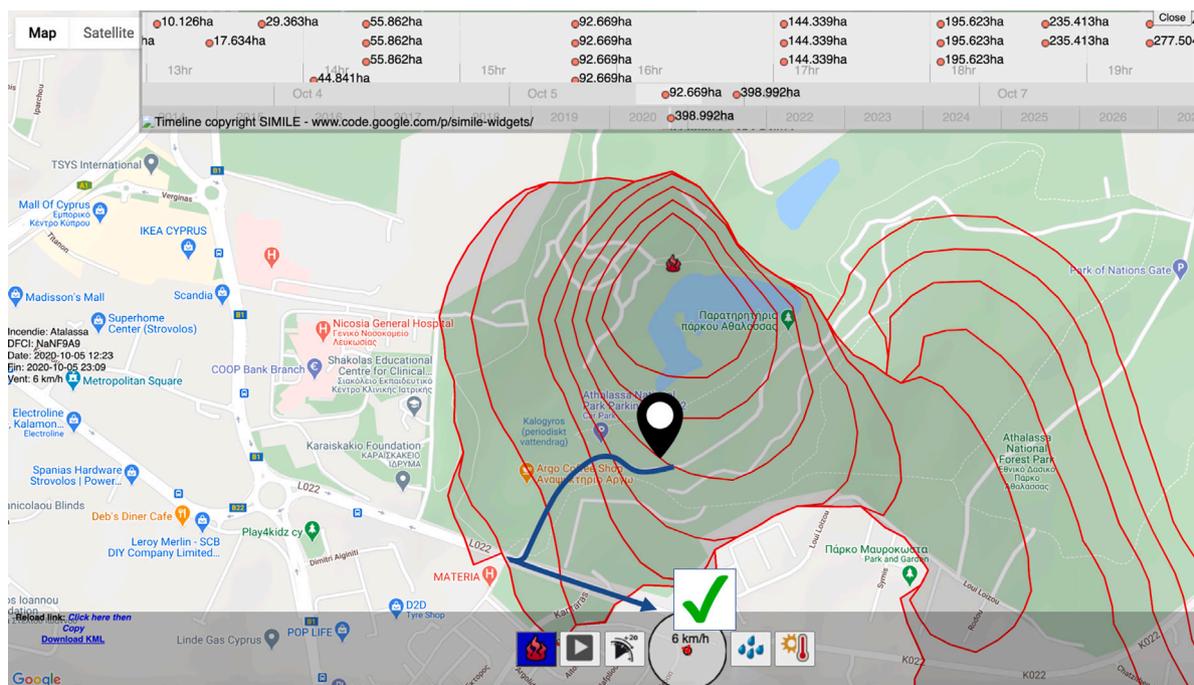


Fig. 6. Evaluation area: Athalassa natural reserve. The ignition of wildfire, participants' initial positions and suggested escape route. Visualizations are produced by the ForeFire fire behaviour modeller [46] and not by the mobile app.

In all the three figures, the wildfire has been manually ignited near the centre of the map, by means of the fire management tool (see Section 4.4), while red polygons show the estimated spread of the wildfire in subsequent 30-minute slots. Please note that these are

snapshots of the modeller tool and not of the mobile app (Fig. 2, left), as the intention was to give to the reader an understanding of the local area under study. In all the Figs. 6–8 at the top, the number of hectares burnt by the wildfire at each hour after ignition are displayed, while at

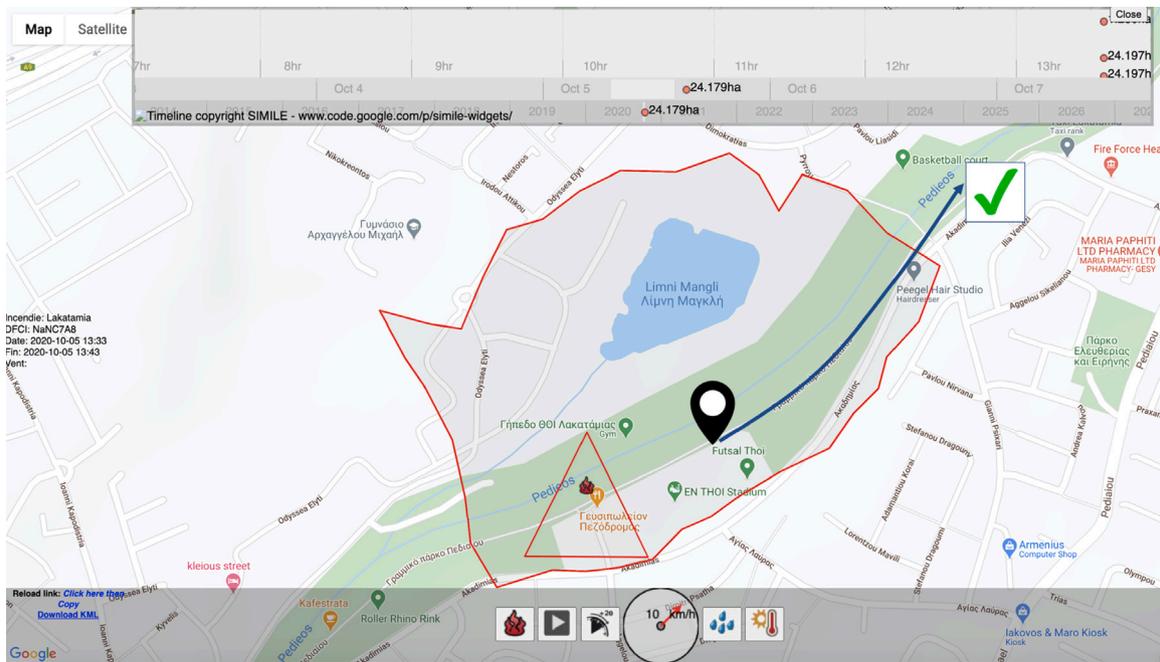


Fig. 7. Evaluation area: Lakatamia linear cycling park. The ignition of wildfire, participants' initial positions and suggested escape route. Visualizations are produced by the ForeFire fire behaviour modeller [46] and not by the mobile app.

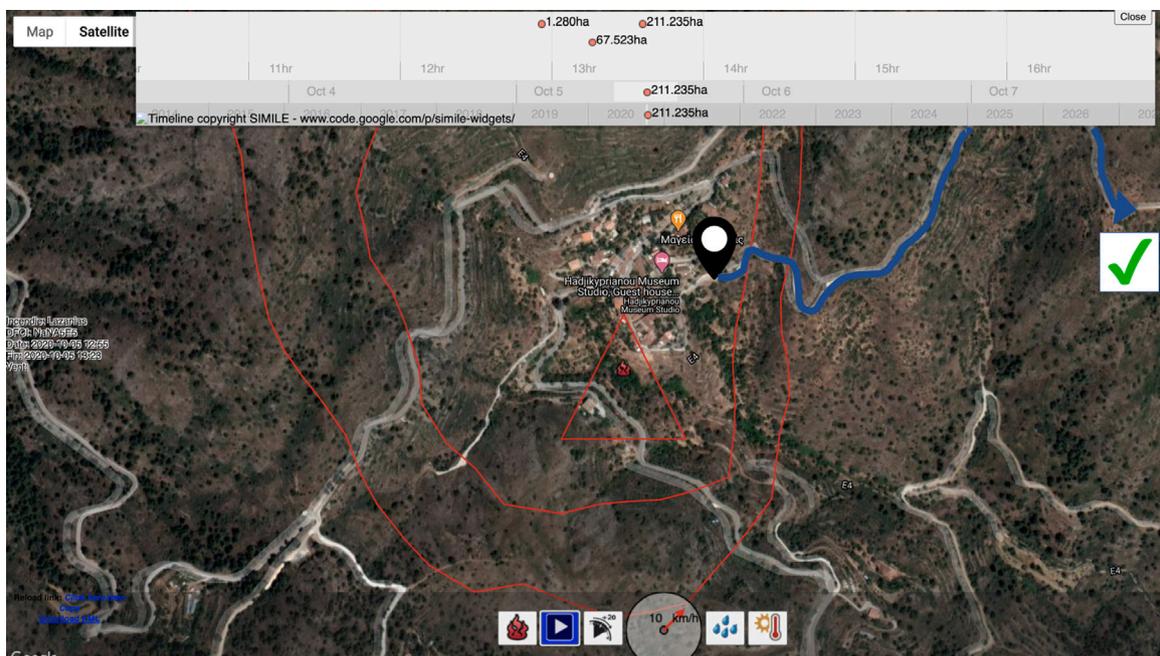


Fig. 8. Evaluation area: Lazanias rural-area village. The ignition of wildfire, participants' initial positions and suggested escape route. Visualizations are produced by the ForeFire fire behaviour modeller [46] and not by the mobile app.

Table 2
Scenarios under study and characteristics/parameters.

Area	Type	Partici pants	Transport mode	Wind	Humidity	Temperature
Athalassa	Natural reserve	17	Walking	6 km/h (east-south)	30%	30° Celsius
Lakatamia	Linear park	16	Cycling	10 km/h (north-east)	30%	30° Celsius
Lazanias village	Rural area	13	Driving car	10 km/h (north-east)	40%	21° Celsius

the bottom, parameters such as wind speed, humidity and temperature are provided. Table 2 shows the characteristics of each scenario under study.

These areas included landscapes of various types, plus humans in different modes of transport: walking (Athalassa), cycling (Lakatamia) and driving by car (Lazanias). Participants were selected randomly as

Table 3
Questionnaire used during the evaluation process.

Question	Type	Responses in area		
		Athalassa	Lakatamia	Lazanias
How easy was the application to understand in general?	Likert scale, from very difficult (1) to very easy (5)	Avg. value: 3.9 St. dev.: 0.9	Avg. value: 4.5 St. dev.: 0.8	Avg. value: 4.1 St. dev.: 0.6
How easy was the application to follow using the advice given?	Likert scale, from very difficult (1) to very easy (5)	Avg. value: 3.6 St. dev.: 0.8	Avg. value: 4.2 St. dev.: 0.4	Avg. value: 3.9 St. dev.: 0.6
Did you feel confident while using the application?	Yes/No	Yes (82%), No (18%)	Yes (100%)	Yes (100%)
Would you keep this app downloaded on your phone?	Yes/No	Yes (94%), No (6%)	Yes (100%)	(92%), No (8%)
Did the application help you escape the wildfire safely?	Yes/No	Yes (100%)	Yes (100%)	Yes (100%)
Did you feel like the application worked the way it should have?	Yes/No	Yes (94%), No (6%)	Yes (100%)	Yes (92%), No (8%)
How likely is it to suggest this application to someone?	Likert scale, from very unlikely (1) to very likely (5)	Avg. value: 4.1 St. dev.: 0.7	Avg. value: 4.7 St. dev.: 0.5	Avg. value: 4.2 St. dev.: 0.7
How likely is it to use this application in a real life scenario?	Likert scale, from very unlikely (1) to very likely (5)	Avg. value: 4.1 St. dev.: 1.2	Avg. value: 4.5 St. dev.: 0.5	Avg. value: 4.3 St. dev.: 0.7
What improvements would make the app more useful, effective and/or user friendly?	Open question	See Section 6.5.	See Section 6.5.	See Section 6.5.
How much time did you need to escape the fire?	Response in minutes:seconds	(for 0.8 km) Avg. value: 8:30 St. dev.: 5:25	(for 1.2 km, via bike) Avg. value: 3:20 St. dev.: 0:55	(for 2 km, by car) Avg. value: 2:20 St. dev.: 0:20
Did you follow 100% the route suggested by the app? If not, why?	Open question	Yes (94%), No (6%)	Yes (100%)	Yes (100%)
Was the route suggested by the app the best one to your knowledge, in order to safely evacuate?	Open question	Yes (100%)	Yes (100%)	Yes (100%)

they were passing by. They were asked to participate in a scientific case study simulating the scenario of a fire occurring near them. The evaluation exercise took place in the afternoon (around 17:00–19:00), coinciding with a high likelihood of free time. They were asked to download the mobile app from Google Play and then follow the instructions given by the app. Afterwards, they were asked to fill a questionnaire, eliciting information about demographics, plus the questions listed in Table 3. As compensation for their efforts, participants received a voucher for free coffee at a popular cafe in the local area.

Forty six people in total agreed to participate in the pilot studies. Their demographic information is shown in Table 4. Gender was equally balanced in Athalassa and Lazanias, but not in Lakatamia, where most cyclists were male. Age distribution was also imbalanced in Lakatamia, since all participants were 16–35 years. The large majority of participants were locals. Most participants were well educated, possessing as diploma, bachelor or master level degree. Some participants were students with secondary level education. The last three columns of Table 3 show the responses of the participants after using the mobile app to safely escape the fire. The large majority found the application easy to use, with little effort required to follow the advice given. The vast majority declared they would keep the app downloaded on their mobile phones. Two participants (females, 43 and 67 years) argued that during a wildfire they cannot feel safe with or without a mobile app as

assistance. One mentioned that *“I would be so panicked that the last thing I would think of is a mobile app”*.

In all 46 cases, the app helped the users to successfully evacuate the area. All but one participant felt like the app worked appropriately, following the route suggested by the app 100%. This one participant (male, 43 years) was confused at the beginning, not being able to follow the suggested route. Most participants considered that they would likely suggest the app to other people and use it in a real-life wildfire situation. All participants agreed that the route suggested by the app was, to their knowledge, the best available for safely escaping the wildfire.

To escape the wildfire, people in Athalassa needed around 8 : 30 minutes to walk the 800 meters to safety (5.64 km/h, see Fig. 6), people in Lakatamia around 3 : 20 minutes to travel the 1.2 km by bike (22.5 km/h, see Fig. 7), and people in Lazanias village required around 2 : 20 minutes to travel the 2 km by car (51 km/h, see Fig. 8).

For the participants on foot in Athalassa, there was a large standard deviation in time (5 : 25 minutes), since older people (51+) needed considerably more time to walk than younger people (16–35) (5 : 50 vs. 13 : 06 minutes). This indicates that the app should consider the physical condition of the user, partly reflected through age although other metrics can be used. Distances travelled and suggested routes calculated by the mobile app are shown in Figs. 6–8, starting from the

Table 4
Demographic info of participants.

Area	Participants	Gender	Ages	Nationality	Education
Athalassa	17	Male (8), Female (9)	16–20 (1), 21–35 (5), 36–50 (6), 51+(5)	Cypriot (14), Greek (2), Kurdish (1)	Diploma (5), Bachelor (10), Master (2)
Lakatamia	16	Male (14), Female (2)	16–20 (10), 21–35 (6)	Cypriot (16), Romanian (1)	Secondary (12), Diploma (2), Bachelor (2)
Lazania village	13	Male (7), Female (6)	21–35 (3), 36–50 (7), 51+(3)	Cypriot (12), Greek (1)	Secondary (2), Diploma (7), Bachelor (4)

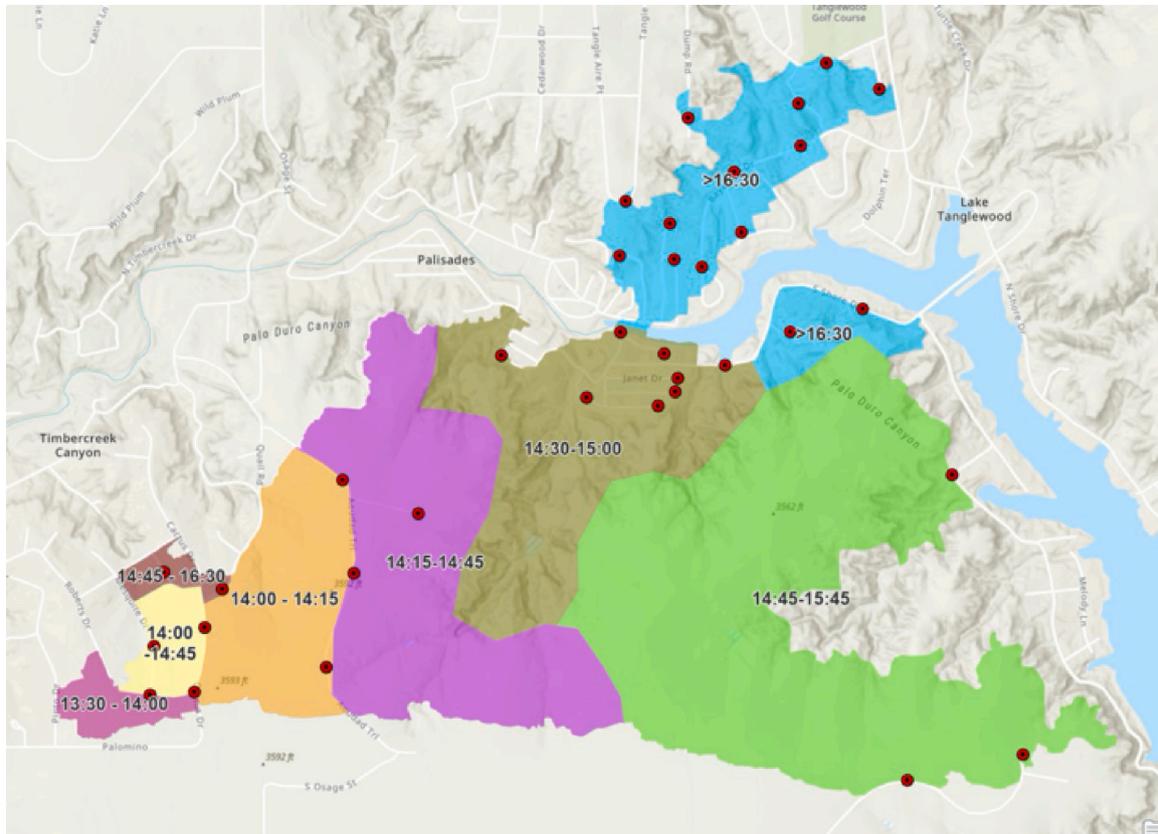


Fig. 9. Progression of the Amarillo wildfire in 15- and 30-minute intervals. The wildfire started at 13:30 at the bottom-left side of the figure. The 35 positions representing humans during our tests, at the point when the wildfire started, are also shown.

black dot (user’s initial position) and ending in the green “tick” icon along the blue line.

5.2. Historic wildfire in Amarillo, Texas

As a second evaluation option, a historic fire was considered, namely the wildfire of the Tanglewood Complex, as it is known, which happened on the 27th February 2011, at the outskirts of Amarillo, Texas. The National Institute of Standards and Technology (NIST), as part of its Disaster and Failure Studies Program, gathered electronic data for the incident as the Tanglewood fire front moved through the Palisades community towards Lake Tanglewood [42]. This wildfire was selected because it was captured in its entirety in GIS software, plus it offers progression intervals of the wildfire every 15–30 min, which is an important feature based on our requirements and design considerations (see Section 3). The progression of the wildfire during its lifetime is illustrated in Fig. 9.

To assess our proposed approach, various positions were drawn on the map, representing humans who could be in the area during the wildfire. Thirty five positions were strategically placed on the map, in order to cover the whole area. These 35 spots were located close to nearby roads of the area, assuming that people would most likely be in proximity to the road infrastructure, especially since the particular landscape of the Amarillo near the Lake Tanglewood is not easily accessible or suitable for walks in nature. For all 35 virtual humans, all possible destinations (i.e. escape routes) were considered, following the area’s road network. In average, each person had 5 candidate escape routes. Considering that the actual wildfire started on the 27th February 2011 at 13:30, we assumed that the people were informed about the wildfire either immediately (i.e. 13:30) or 30-minutes after (i.e. 14:00) or one hour after the wildfire’s ignition (i.e. 14:30).

The Amarillo wildfire had a propagation speed of 2–3 km/h and we considered 20 min as the minimum time duration for high risk. Slope was not considered since it was a relatively flat surface, however

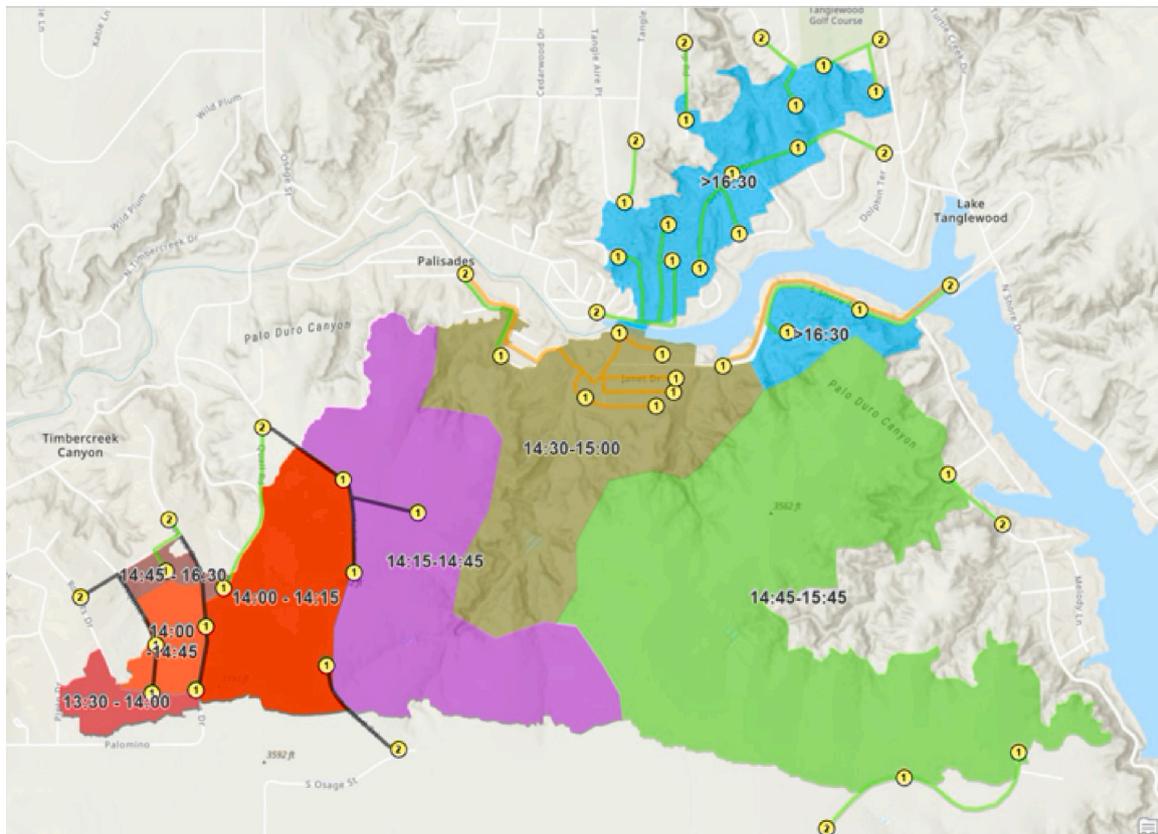


Fig. 10. Escape routes proposed by the EscapeWildFire system during the Amarillo wildfire.

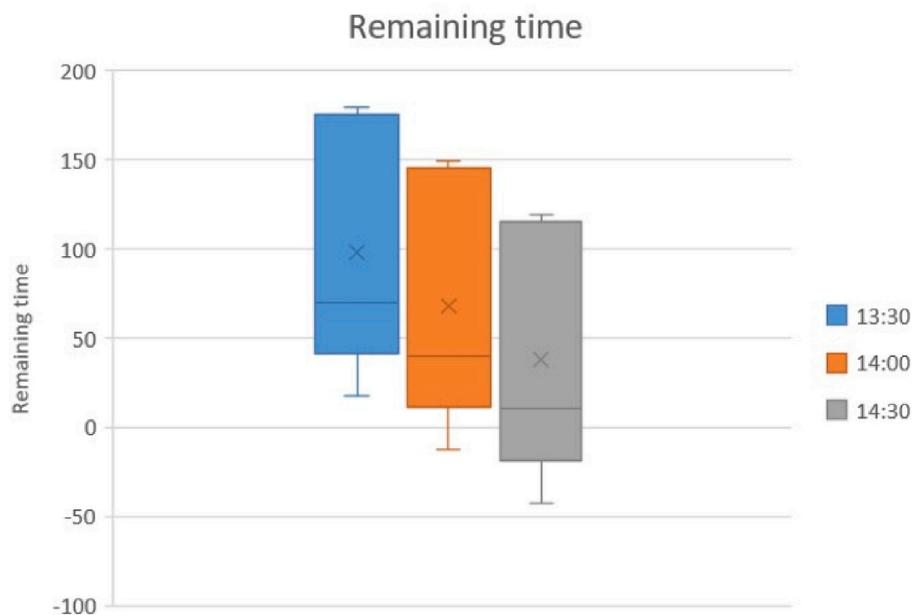


Fig. 11. Distribution of the time to safety by the best escape routes proposed by the EscapeWildFire system during the Amarillo wildfire.

wind was considered since it was strong during the event, reaching 30–35 km/h speed with an east-north direction [49]. Various escape routes proposed by the EscapeWildFire system are visualized in Fig. 10. As the study results suggests, from the 35 points selected, only 27 people (77,14%) would have reached a safe location if they started evacuating

at 14:00, i.e. 30 min after the wildfire’s ignition. In case there was a delay of one hour after the ignition of the wildfire, then only 19 people (53,71%) would have been able to reach safety.

Finally, Fig. 11 depicts the distribution of the *time to reach safety* by the best escape routes proposed by the EscapeWildFire system during

the Amarillo wildfire (i.e. “remaining time” on the y-axis), considering the 30-minute scenarios of delay to start evacuating (x-axis). Values below 20 min remaining time indicate a high risk. For the case of 14:00, this means that 7 people (20%) will have minimal time to evacuate while 1 person (3.5%) will likely die. For the case of 14:30, 10 people (28%) will face extremely high risks while 6 people (17%) will likely die.

6. Discussion

This paper has presented a complete solution to the problem of assisting people to safety during wildfires by evacuation. Various technologies have been combined in order to build a system that supports the creation of escape routes that lead to safety. The evaluation focused mostly on the correctness and feasibility of the proposed system (both Cyprus and Amarillo studies), touching upon human factors and aspects such as acceptance and usefulness (mostly Cyprus study). Through this efforts, various future user needs and requirements have been recorded and are provided in this section as recommendations for similar systems and approaches.

6.1. Correctness and accuracy

Regarding correctness and feasibility, the proposed system worked correctly in all evaluation areas and landscapes, both in Cyprus and Amarillo, Texas. The backend of the EscapeWildfire system was used only in the case of Cyprus: the fire management tool added new wildfires precisely, while the Web server communicated correctly with the mobile apps of the participants to show the fires and suggest escape routes. In the case of Amarillo, the backend was not considered since the progression of the historic wildfire was captured in GIS [42].

Concerning the Cyprus study, all participants agreed that the routes suggested by the app were the best available escape routes to their knowledge (see Table 3) and also agreed that the app helped them escape the fire safely. All but two participants (95%) declared that the app worked the way it should have. Although the routes suggested in these test cases seemed to be the best available, the app works well in areas where the roads are properly defined because the HERE map provider service needs to calculate possible routes based on existing road infrastructures. Inside forests and natural reserves, this might be a challenge. We noticed some difficulty in calculating routes inside the Athalassa natural reserve. Concerning the Amarillo study, the routes suggested by the app also seemed to be the best ones. However, route calculation works well only when the user is located close to a road infrastructure. This is a limitation of the system implemented.

The ForeFire fire propagation prediction model has not been evaluated in this paper, but it has been extensively evaluated both in simulation [46,50] and in real-world wildfire situations [51,52].

Our findings suggest that our evacuation modelling assumptions (i.e. evacuation velocity, see Table 1) were underestimated, compared to the actual evacuation outcomes from the Cyprus study (see Table 3). This observation reinforces the argument that conventional evacuation simulation models may be overly optimistic and that realistic behaviours need to be accurately simulated [22,53], employing archetypes of behavioural patterns of people in such situations [25, 35]. In the example of the Australian bushfires [31], various types of discrepancy were observed between expected and actual behaviour: under-estimation of danger, passivity, denial, over-estimation of capabilities, etc.

Finally, the study of Amarillo indicates the importance of real-time alerts and notifications as soon as the wildfire starts progressing. Every minute of delay in respect to starting evacuation increases the probability of casualties and increases significantly the risks for the people to be exposed to the wildfire.

6.2. Acceptance

In terms of acceptance and usefulness, it was mainly assessed during the Cyprus study. 95% of participants would keep the app on their mobile phones, while 93% felt confident using the app during the simulated wildfire event. The latter should be considered with caution, of course, since it was impossible to simulate a life-threatening experience and record actual observations. In a Likert scale of 1 (very unlikely) to 5 (very likely), participants gave a score of 4.3 (likely to very likely) to the question of whether they would use the app in a real-life wildfire situation. It was observed that older people (51+, Athalassa and Lazanias) found it hard to trust mobile apps, especially in emergency situations. This was not the case for younger people, an observation which was particularly evident in the test case of Lakatamia (cyclists, 16–35 years old). Nevertheless, participants gave a score of 4.3 (likely to very likely) for the question of whether they would recommend the application to someone. Remarkably, the two participants who claimed they would not keep the app on their phones, responded that they would likely suggest the app to others.

6.3. Ease of use

Concerning ease of use, it was also mainly assessed during the Cyprus study. Participants scored 4.1 for the question whether the app was easy to understand (Likert scale, 1: very difficult to 5: very easy). There was a difference in the scores between the evaluation areas. People in Athalassa found it more difficult to understand the app (score: 3.9) than people in Lakatamia (score: 4.5) and Lazanias (score: 4.1). As mentioned before, older people had difficulties in using the app and required more time to get familiar with it at the beginning of the process (first 2–3 min). Participants gave a score of 3.9 for the question of how easy it was to follow the advice given by the app. The lowest score (3.6) occurred in Athalassa (people on foot) and this perhaps reveals some difficulty of navigation outside of areas with designated roads. On the other hand, people on bicycles (Lakatamia, score: 4.2) and in cars (Lazanias, score: 3.9) experienced clearer and easier to follow instructions, i.e. it was easier for them to orientate and navigate the suggested route.

Aspects of facilitating orientation are discussed in Sections 6.4 and 6.5 below. Nevertheless, all 46 participants of the Cyprus study eventually escaped the wildfire safely by using the app, following the routes visualized in Figs. 6–8.

6.4. Limitations

The proposed system and the case studies performed only indicate how a small number of subjects could utilize a mobile app to assist them evacuate safely some area because of the risk of a nearby wildfire. This paper does not intend to shed light into the existing challenge of better understanding collective evacuation decision-making and behaviour in fire-prone countries such as USA and Australia [22,54], where much data is already available [31]. Also, the proposed system does not consider how to convince people to take action (i.e. response time), since a warning has been issued (i.e. warning time). It is only assumed that people will start acting as soon as a warning has been received, which is not always the case [24,25].

A limitation could be the fact that the exact location and time of ignition of the wildfire needs to be manually entered to the system (i.e. fire management tool, see Section 4.4) by a system operator. The use of advanced technology (e.g. drones, satellites, forest sensors) to automatically detect and locate wildfires is beyond the scope of this work, but it could be easily combined with our proposed system.

In terms of forest fire predictions, a number of limitations exist due to the datasets or models employed in the current version of the proposed system. A conservative parameterization of ForeFire code [46] was selected in the EscapeWildFire system applied in the study of

Cyprus, for reasons of robustness, using the most common fire velocity model (Rothermel [47], used in the US Forest Service since 1990) and the CORINE land dataset [48] (EU-provided land cover at 80 m resolution). Nevertheless, more detailed land-use datasets and more specific fire velocity models may be considered and will likely lead to better forecasts. Other candidate models include PHOENIX [55], Wildfire Analyst [56], BehavePlus [57] (includes 40 fire models) and FlamMap [58] (used widely in the USA). Interestingly, the BehavePlus model (version 5) contains also a *safety zone* model, where the needed minimum distance between a person and the fire front is calculated. This feature could be compared and/or combined with our system's design in future work.

Another limitation of both the Cyprus and Amarillo studies is the fact that the scenarios selected (see Section 5) were relatively simple, in which users had reasonable time to evacuate (except when we delayed the notification about the wildfire in the Amarillo study by 30 and 60 min). Also, the candidate routes to evacuate numbered 4–7 in all cases/scenarios, thus the correctness and accuracy of the mobile app in terms of suggesting the best route (discussed in Section 6.1) must be taken with some caution by the reader. Moreover, regarding calculation of the best escape route, the values in Table 1 should be personalized for each user and mode of transportation employed.

Further, an important limitation is that our system does not embrace or provision solutions for people with disabilities. We discuss some recommendations below on how to provide help and support to this vulnerable group of users, which is a key priority to us.

Moreover, our studies have not considered the need for evacuees to distribute themselves optimally over available routes [59]. This issue might be more relevant for evacuating cities and neighbourhoods, but it could still be the case for some wildfire scenarios.

Another important limitation is the fact that available commercial earth mapping tools provide calculations for escape routes based on the existing road infrastructure, which might not be an option in a situation of a wildfire, where the user needs to traverse through forest for the optimal evacuation option. It should also be noted that telecommunications might be down during the wildfire, bringing Internet outages that would affect the proposed solution [60]. This is actually a possible high risk, implying that the proposed system might need to be implemented together with more resilient telecommunication infrastructures in WUI areas.

Finally, we did not test the possibility of a real-time change in the proposed evacuation plan. An example for such a need could be a sudden and unexpected wind change, which was considered a “major cause of the deaths that resulted from the 7 February bushfires” in Melbourne, Australia [31].

6.5. Recommendations

One of the principal benefits of the evaluation process taking place in Cyprus was the collection of useful suggestions by the participants for improving the system, especially in regards to the proposed design of the mobile app (discussed in Section 3.2), which was the point of interaction with the users. Importantly, it was evident that older people required better accessibility features on the mobile app (e.g. larger buttons, vivid colours, flashing directions and arrows, verbal/textual directions and visual features, etc.). Perhaps such features could appear only when users have certain age (e.g. above 50) or have vision problems. In general, users seem to prefer minimalistic design and features. Some found the buttons for “turn-by-turn” or “directional” instructions before entering the map interface confusing. Also, the “show map” button was a bit confusing for three users, who preferred to enter the map immediately as soon as they opened the app and take action. Two participants asked for instructions on how to use the app after downloading it, like a quick tutorial. There should be a “skip” button for this tutorial so as not to waste time in a real, life-threatening situation.

Another important requirement, mentioned by six participants at the Cyprus study, was the need to accurately define and assist the orientation of the user [22,61]. This could be indicated by the phone compass showing the magnetic north whilst adjusting the map to the user orientation. Showing the historic movement of the user will also facilitate orientation. The built-in compass of many mobile phones could also be used in areas without GPS coverage. In this case, calibration procedure should be in place to avoid erroneous direction.

Two participants of the Cyprus study asked to indicate on the mobile app the time before actual danger, although the authors consider that this could add pressure and create panic. More elaborate work on proper design of mobile apps for emergency situations is needed, an aspect related to the research area of evacuation modelling [62], where behavioural and physical issues associated with human behaviour in fire and crowd dynamics need to be considered [31,53] (see also Section 6.6 below).

Some additional requirements recorded by participants of the Cyprus study in response to the question “what improvements would make the app more useful and user-friendly” include:

- *Way-finding using landmarks* (e.g. mountain tops, hills, buildings), useful for some pedestrians. Use of well-known landscapes for navigation would be important in forest areas where online map provider services cannot properly calculate escape routes [61].
- *Dealing with confusion and wrong turns*, because people may be nervous and make mistakes. Considering this, the mobile app can suggest not only the fastest route but also the least error-prone one. That is, even if users get confused and make the wrong turn, they would not be put in too much jeopardy. In respect to this, perhaps the app could assist via a sound or a vibration mechanism, which could alert them if they took the wrong path.
- *Assisting people in need*, i.e. locating humans who are close to the suggested escape route, e.g. people with disabilities, avoiding to create life-threatening risks to the users.
- *Proactive information about risks in each area*.
- *Alternative routes* calculated by monitoring users during evacuation to avoid congestion that would delay the evacuation process. Monitoring could also create risk scores and alerts for people in large danger, which would help firefighters to prioritize and act more effectively e.g. send helicopters to key locations. Privacy issues might arise in this case and need to be carefully considered. Two participants asked explicitly for the possibility of “authorities to know my movements in real-time”.
- *A personalized speed of evacuation* for each user, depending on user's overall expected fitness, which could be partly derived from his/her age. Personalization could generalize to the type, frequency, amount and way in which information is provided and presented to the user, during the evacuation processes. Different archetypes of users [25] implicate different strategies in sharing information. This is a topic for future research.
- *Automatic notification for nearby wildfires* before they become life-threatening.
- *Exploitation of the civil defence infrastructures*, e.g. include routes to nearby shelters [23,40], sirens with real-time instructions, etc.
- *Use of the app not only by citizens but also by rescue personnel and firefighters*, e.g. to find the safest and more efficient way to approach the wildfire. Evidence suggests that firefighters' tenability has a strong influence on wildfire's suppression [63].

Comparing the recommendations above with the requirements listed in Section 3.1, they are very much in line and supplement the basic must- or should-have ones, thus we consider them for future versions of the EscapeWildFire system. An important feature mentioned by officers of the Cyprus fire authority was the modelling not only of wildfire's propagation but also the smoke's diffusion through hills and mountains. Wildfire smoke is recognized as an important health hazard [15]. There

is evidence that wildfire smoke exacerbates chronic lung disease [64], while it was a reason for human casualties during recent wildfires in Cyprus.¹⁴

Summing up this section, the list of recommendations discussed above, together with the list of limitations discussed in the previous section, illustrate the overall complexity of the problem under study, and this should be clear to the reader. Much caution needs to be taken by any organization or agency decides to follow the proposed approach and implementation as discussed at this paper. One of the contributions of this paper is to identify and communicate those challenges to the interested and relevant stakeholders, explaining as much as possible the requirements, aspects to consider and overall implications. We do not want of course to discourage anyone from following this path, which can be life-saving for hundreds of humans every year, but the design and development of any project at any region around the world needs to be careful, holistic and accurate, something that requires considerable resources in time, effort and money.

6.6. Future work

As for future work, efforts will mainly focus on improving the mobile app along the lines of the feedback received by the participants and observations of the authors (see Section 6.5 above). Land type distribution data with higher spatial resolution than the CORINE LandCover dataset [48] will be acquired, plus we intend to investigate various fire velocity models, towards better accuracy on modelling fire propagation. Modelling of smoke's diffusion in the 3D space will also be considered. A comparison of the island of Cyprus with the island of Corsica, for which a relevant case study has been performed in [54], would be an interesting initiative.

Multiple modes of transport and dynamic escape routes will be supported, performing re-routing along the way based on the actual status of the wildfire and all relevant contextual information collected, e.g. sudden change in the wind direction or speed.

A more elaborate evaluation process will take place after the recommendations have been implemented, in more realistic and challenging physical scenarios and landscapes, considering also other historic wildfires. Participants of different ages will be considered in each scenario, to avoid imbalanced data. Also, night situations have not been considered, which could be cumbersome to accomplish an evacuation. The impact of night-time in evacuation efforts needs to be included to the escape route algorithm, proposed in Section 3.3.

Further, future work will consider more personalized values of expected transport speed depending on someone's fitness or vehicle type. Support to people with disabilities will be considered. In this regard, the system may support disabled people to use available transportation options to reach the nearest emergency airlift locations, provided by emergency personnel.

Moreover, future work should consider how people react under high-pressure and panic scenarios. Apps should be highly user-friendly to assist people under panic attack. Generally, the research area of human-computer interaction modes for emergency apps [65], together with the research area of evacuation modelling [22,62], both have much space and potential for further investigation. Virtual reality can be promising for creating more realistic scenarios [66,67], allowing to better examine the behavioural and physical issues associated with human behaviour in wildfires and crowd dynamics [53]. To emulate panic, we could transform the evacuation effort into a serious game, providing real-time info of how the wildfire is approaching every second, to increase pressure. Psychologists and sociologists need to get involved to the process.

¹⁴ BBC News, Second firefighter dies tackling Cyprus forest fires. <https://www.bbc.com/news/world-europe-36583544>.

Finally, we will investigate the possibility that the mobile apps will communicate the users' locations and suggested routes to the backend web server, in order to make a coordinated and orchestrated effort for crowd evacuation, avoiding congestion and bottlenecks. This project is part of the Cyprus national strategy for disaster management and response and the deployment of the presented system all around the country of Cyprus will take place during the coming months, together with the support of the local fire authorities, Department of Forestry and Civil Defence.

7. Conclusion

This paper examined the potential of mobile applications to be employed to assist people to escape wildfires in real-time, by means of using and evaluating EscapeWildFire, a system for suggesting evacuation paths to mobile phone users in real-time. Two different evaluation scenarios were considered: (a) Different areas of the island of Cyprus as case studies with simulated wildfires and actual users and (b) A historic wildfire that occurred in Amarillo, Texas in 2011. Results in both cases showed that mobile apps can effectively be employed to assist people to escape wildfires, but their use is heavily dependent on a backend system that supports the precise modelling of the wildfire. The time between the wildfire outbreak and the notification reaching the user is crucial for the people's safety. Various recommendations for improvements have been recorded based on either the feedback of participants in the case studies or the observations from the Texas wildfire. The code of the system is available as open-source; the authors encourage fire authorities around the world to consider this opportunity and to adopt this approach.

Data availability

The source code used for the implementation of the EscapeWildFire system is available in GitHub, listed as reference in the manuscript¹⁵ together with complete user manuals and instructions.

Acknowledgements

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