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Visualising Agent-Based Model Outputs to Enhance Decision-Making in Search and Rescue Operations

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Abstract:

In search and rescue (SAR), time is critical, and successfully finding a lost person in the least amount of time is the goal. Part of a successful search is the development of accurate and relevant search areas. Planning these search areas for lost people can be improved by developing and using spatial models. Spatial models allow for the prediction of a lost person's movement through the interaction between human navigation behaviour and the underlying terrain. However, they are not often used in real-time SAR. This research looks at spatial models in SAR and outlines the development of an Agent-based model for more accurate search planning and rapid decision-making. The output of the model is discussed, and strategies to engage SAR in the uptake of spatial modelling results are outlined. By incorporating spatial modelling results, it is hoped that search areas can be designed more effectively, which will, in turn, improve the outcomes for lost people.

Keywords: search and rescue, agent-based model, cartography, decision-making

1. Introduction

Maps and spatial information are crucial for search and rescue (SAR). Specialist SAR officers use maps to assess the area a person is lost in, look for locations where the person is likely to be, and use topographic maps to design search areas. The development of search areas is key to a successful and timely search. Accurate search areas can mean the person is found in hours rather than days. To improve search area planning, practical tactics can be employed, such as reducing the size of the search area by better geographic assessment of where the lost person is likely to be located (Doherty et al., 2014). SAR personnel also use a spatial model called the ring model to assist in developing search areas (Koester, 2008). The ring model guides search planners on the distance a lost person may be away from their last known position (LKP) based on summary statistics from previous search incidents.

To further improve search area planning, spatial models can be used that incorporate lost person behaviour and details of the underlying terrain to identify likely paths taken and the highest probability areas that a lost person may be. Spatial models are often applied to assist in decision-making and solving complex problems (Darvishi & Ahmadi, 2014), and they can be applied to SAR. There have been numerous spatial models developed for use in SAR (Almujalli & Altuwaijri, 2023; Brown et al., 2019; Dacey et al., 2022; Drexel et al., 2018; Hashimoto & Abaid, 2019; Hashimoto et al., 2022; Lin & Goodrich, 2010; Mohibullah & Julier, 2013; Nguyen et al., 2023; Papić et al., 2024; Rossmo et al., 2019). Despite their ability to apply probability to a lost person's location, using spatial models in real-life SAR incidents is not commonplace. This is due to several factors, including SAR continuing to do what already works and a potential hesitation to use new technology in time-critical situations.

In order to assist in the development of more accurate search areas, this research developed a spatial model that incorporates human navigation behaviour and environmental terrain data. The model can be used to predict a person's likely movement within a wilderness environment. The model runs over thousands of iterations to simulate the possible movement of a person and determine the probability of the person travelling a particular route or ending in a particular location based on time and distance travelled. In addition to outlining the model, the methods of output visualisation are discussed to improve the likely uptake of the model output for use in SAR incidents. The methods discussed include designing the output to be familiar to SAR officers, improving interoperability and providing the output in a format easily translated into their current work practices.

This paper looks at how the spatial model's output can be designed to incorporate probability-based, data-derived information for the development of search areas. Including this information in rapid decision-making is anticipated to improve situational awareness and provide clarity in stressful situations. By developing the model output for

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consideration in search area planning, it is hoped that search areas can be more targeted to the specific lost person and that the timeframe of a lost person being in the wilderness will decrease, improving their likely outcomes.

2. Spatial Modelling for Search Area Development

When a person is unable to be located in the wilderness, part of planning the search involves the creation of search areas, which are determined based on a multitude of different factors. These factors considered by SAR officers include the distance a person likely travelled, the terrain, deduction through learned facts and clues, and statistical information (Australian National Search and Rescue Council, 2023). Search area planning aims to determine the most likely areas in which a lost person may be located. The determination of a lost person's location can be undertaken through the use of spatial modelling.

Australian SAR agencies use the ring model to assign probabilities to search regions based on quartile distance statistics using buffer rings from the LKP, which is a probability circle by subject categories based on the model developed by Koester (2008) (Figure 1). Data from previous lost person incidents are collected via the International Search and Rescue Incident Database (ISRID) to inform the model (dbS Productions, 2011). These incident data are divided into 41 categories, including children in different age groups, people with dementia and despondent people in urban and wilderness settings, and hikers, skiers and hunters in wilderness incidents (Koester, 2008). While the ring model is easy to use and provides fast results without additional information, it is based solely on statistical data. It does not incorporate terrain data apart from mountainous versus non-mountainous terrain (Drexel et al., 2018). The ring model does not consider the additional movement of a lost person, assuming that the subject is no longer moving by the time a search begins (Sava et al., 2016). Additionally, the ring model does not include demographics in the lost person behaviour categories, but Koester (2008) acknowledges that the possible inclusion of gender differences needs further consideration. Adding to this model by determining more specific regions of the potential location of a lost person is possible using more advanced spatial modelling.

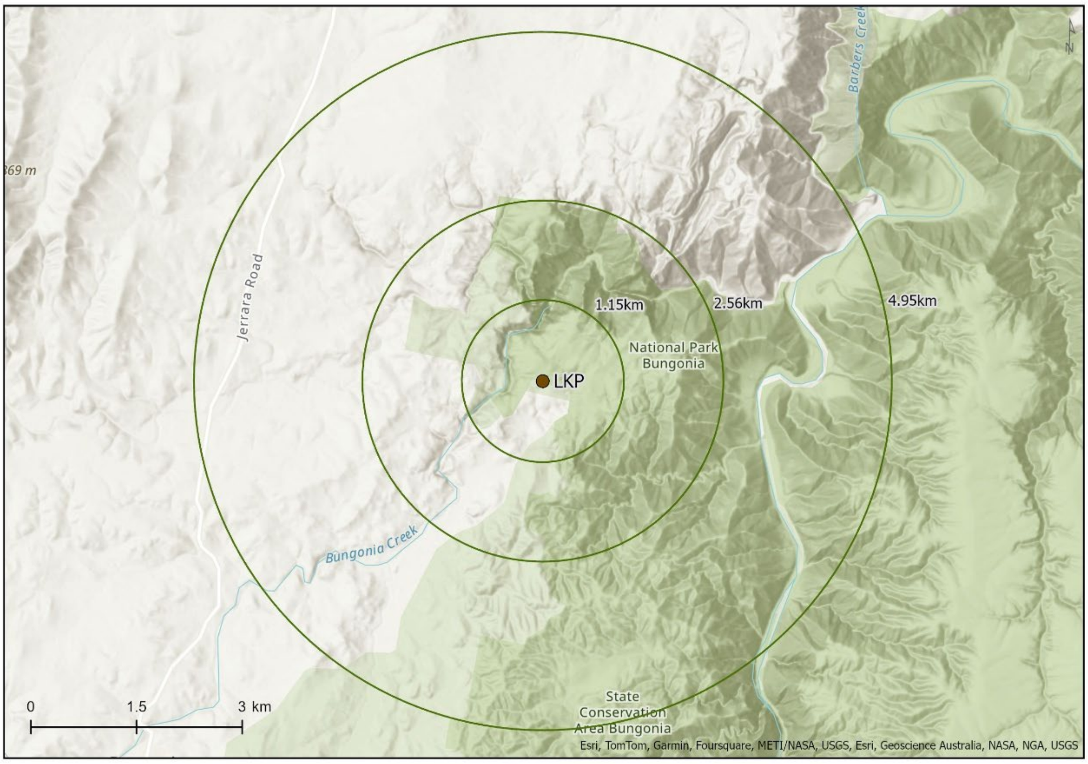

Figure 1. Example of the ring model with the Euclidean distances from the LKP for the hiker category

There is no evidence to suggest spatial models beyond the ring model are currently used operationally for search area determination in SAR. This lack of uptake may be due to unfamiliarity and insufficient expertise in the use and possibilities of Geographic Information Systems (GIS), which may be a deterrent to expanding GIS technologies in SAR (Rose, 2015). Many SAR operations involve spatial data; however, its use has some limitations in these time-critical situations. These limitations include the cost and usability of the software and human resources, such as the investment in personnel to learn the technology or ongoing reliance on expert users (Rose, 2015). SAR occurring in wilderness settings are often in remote areas without access to computer servers, standard communication channels or reliable power (Ferguson, 2008). These conditions also contribute to the hesitance of using spatial modelling in time-critical situations for SAR, which makes their use challenging. However, with the mobile industry maturing at a rapid pace, utilitarian mobile applications such as navigation using Global Positioning Systems (GPS) development are expected to continue to grow into the future (Wang et al., 2018), indicating that developments that were not feasible some years ago may be more feasible now and into the future.

3. Agent-Based Modelling in Search and Rescue

Agent-based modelling (ABM) is a spatial modelling technique that incorporates three elements: an agent, the environment and interactions between agents and the environment (Darvishi & Ahmadi, 2014; Macal & North, 2010). Recognising the individual's importance and decisions makes ABM a powerful strategy for creating simulations to test theories, particularly those not easily described by mathematical formulae (Crooks et al., 2018). The agent model framework used to develop an ABM can control the agent's behaviour based on strategies that affect the agent's movement. In a SAR setting, these strategies can reflect the possible changing goals of a lost person, which may be driven by the perception of the environment by the agent (Lin & Goodrich, 2010; Mohibullah & Julier, 2013). Additionally, this ability of the environment to influence agent behaviour makes ABMs ideal for use in SAR.

The use of an ABM in this project was an effective technique to incorporate two of the most important elements considered by SAR officials when searching for lost people: (1) the terrain and (2) the lost person’s behaviour. The autonomy of an agent (lost person) and their ability to make decisions based on the system's state (environment) at the time is one of the critical features of an ABM (Macal, 2016), making it a logical choice for modelling in SAR. The ABM was developed in three stages: data collection, terrain analysis and model building. The first stage collected data on human navigation behaviour when hiking in the wilderness.

Data was collected from a range of people interested in hiking in one of four study sites around Australia. Initially, a link to a questionnaire was posted on social media, requesting people who might be interested in taking a hike for research complete the questionnaire. This questionnaire requested demographic information such as age, gender, wilderness experience, physical condition, and a test of their sense of direction using the Santa Barbara Sense of Direction Scale (Hegarty et al., 2002). Following this, participants were contacted via email requesting they register for one of the pre-planned walking activities. These activities consisted of meeting the researcher at a meeting point, walking to a designated turnaround point, and back while carrying a GPS tracker. GPS tracks were inspected visually to look for behavioural patterns, such as travelling off-track, shortcutting and backtracking. These GPS track behaviour characteristics were then added to the datasets for further analysis. The aggregated data was then analysed in R using Generalised Linear Modelling followed by Odds Ratio (R Core Team, 2023). The test allowed the assessment of what variables are correlated and what variables can be used to predict the outcome of other variables. For example, different dependent variables such as gender, age group and physical condition were tested against the likelihood of staying on formed tracks.

The second part of the ABM development included terrain analysis, assessing which terrain features influenced the movement of people in the wilderness. It was determined that the terrain surfaces to be included were elevation, calculated through slope and terrain ruggedness, and vegetation density. Other terrain features that can affect the navigation of a person in the wilderness were also included, such as elements that encourage movement in a particular direction, including natural funnels or terrain features that may be impassable. The wilderness also has terrain features that can greatly impact a person’s route choice. These include obstacles, such as large waterbodies, cliffs, gorges and very dense vegetation, which can force a change of route or influence distance and speed. Additionally, linear features were included, such as tracks, watercourses, fences, coastlines, ridgelines, and distinct changes in vegetation type. These linear features can assist in navigation and provide an easier route.

Finally, the navigation behaviour determined through the project and the terrain data were combined in an ABM to accurately reflect the likely movement of a person in the wilderness. The navigation behaviours were used to develop rules that govern the agent's behaviour based on the specific demographics of the agent as well as the underlying terrain and the overall goals of the agent. The model is set with parameters specific to the lost person and a degree of randomness, running over thousands of iterations. The model output was then spatially analysed to create probability maps of the likely lost person's movement and location after a specific period.

4. Agent-Based Model Output for Search and Rescue

The ABM developed in this project can provide two outputs: point data of the possible location of the lost person after a designated amount of time or linear data to demonstrate the likely paths taken. Therefore, the final output of the model can either display likely track sections or areas of high probability, depending on the model parameters. For example, a person who stays on track over thousands of iterations will produce an output of the most likely traversed tracks being displayed through kernel density analysis (Figure 2). The model output of a person likely to have travelled off-track is better displayed as an areal map of possible locations viewed as a probability map (Figure 3).

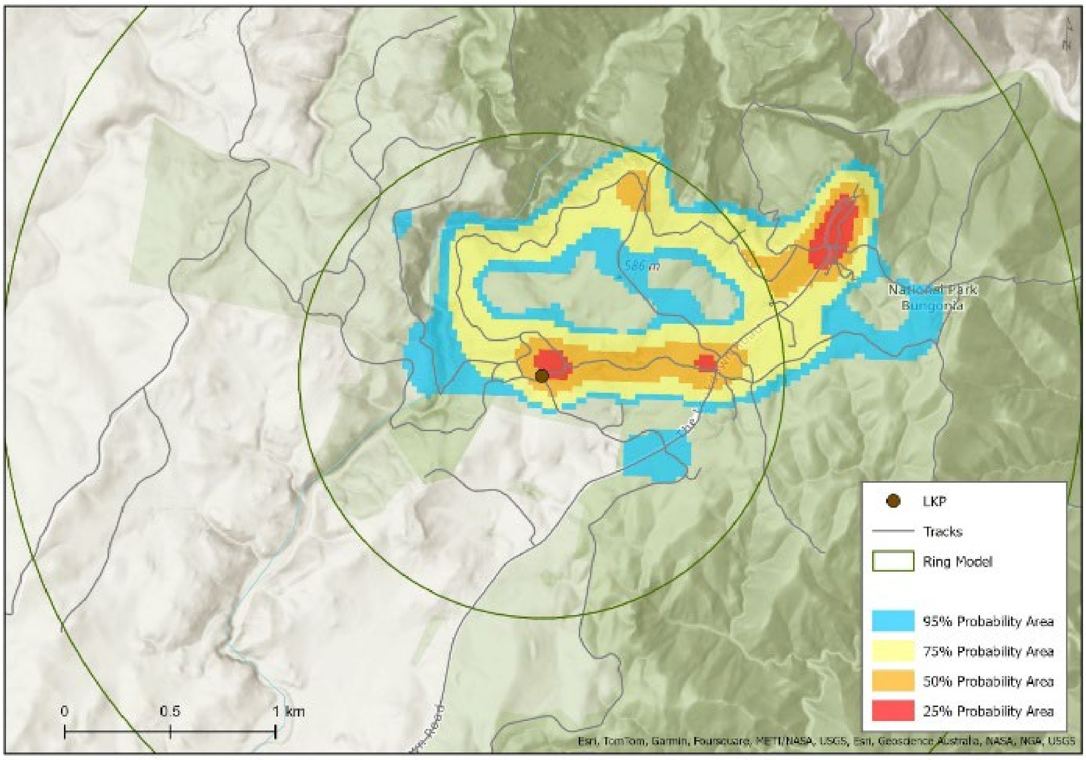

Figure 2. An example of a linear probability map indicating track areas where a lost person may have travelled during a specified period

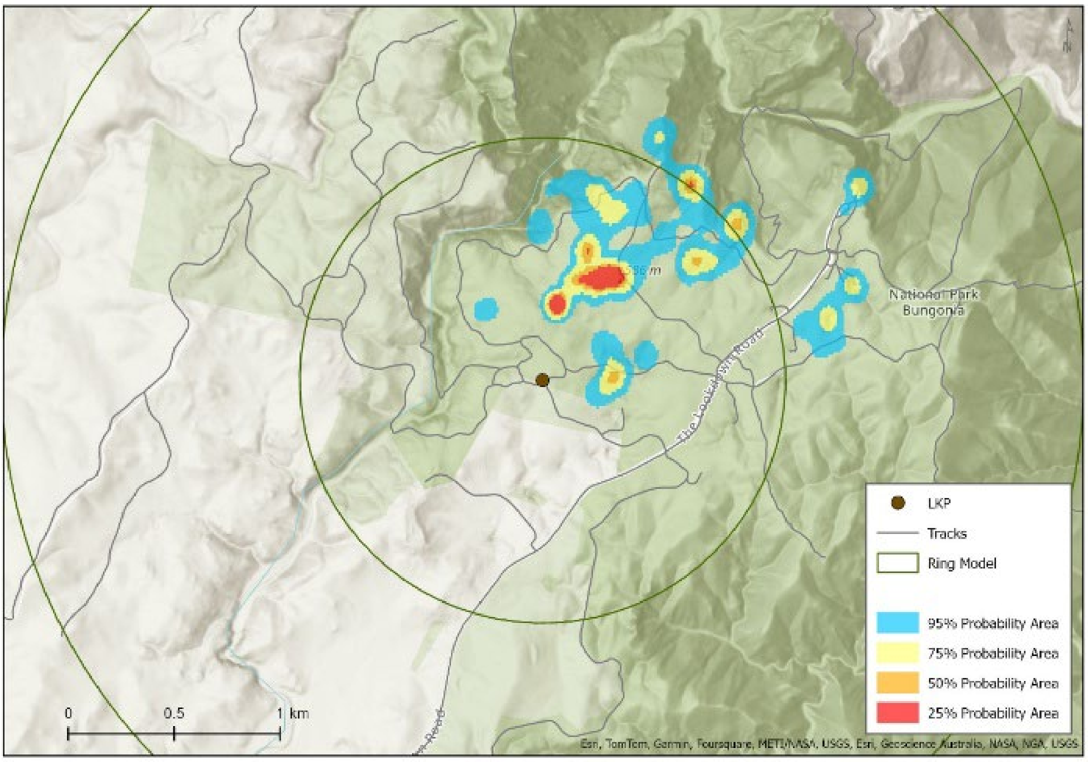

Figure 3. An example of the areal probability map with off-track areas where a lost person might be located after a specific amount of time lost

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To increase familiarity with the model output, the produced probability maps are designed to reflect the output of the ring model, which divides the areas of finding the lost person into quartiles. The output has been designated into those same quartiles in order to increase the understanding of the output. In current searches, the smallest buffer ring is searched first, followed by the second, extending outwards. The division of the kernel density analysis into similar quartiles allows for translation between the ABM output and the ring model output. The colour ramp has been designed to clearly distinguish between each quartile and uses appropriate colours for colour vision impairment. The colour scheme resembles a heat map in which red is the highest probability, dropping to orange, yellow, and then blue, which is the 75-95% probability area. There is no standard colour scheme within SAR; therefore, the colours can easily be altered to meet SAR preferences.

The output from the model can be provided in differing formats to provide the most familiarity to the SAR officers. The output can be provided as a transparent layer on hard-copy maps with topological base maps, which can be used for planning purposes. Additionally, the output can be provided electronically in a format that can be consumed by the SAR GIS software of choice. For example, many SAR officers in Australia use Google Earth, so output can be converted to polygon data and provided as a KML. For users of ESRI ArcGIS, model output can be shared as a project package, shapefile or featureclass. Providing the model output in the most appropriate form to SAR officers can go a long way to assuring the use of the output in the consideration and design of search areas.

In addition to making the map as user-friendly and familiar as possible, the uncertainty that is introduced through the model needs to be communicated in a way where the uncertainty is understood and decisions can still be made. This uncertainty can be established through the explanation of how the ABM works, the use of terminology such as "probability", and the emphasis on the model output being considered as an additional tool in search area planning rather than technology that can identify the exact location of a lost person.

The use of an ABM can provide additional information to assist in search planning; however, multiple factors inhibit their uptake that need to be addressed to generate a model that is not only effective but can be integrated into current SAR practices. In time-critical situations, humans tend to rely on their intuition rather than structured decision-making processes (Ting & Zhou, 2008). This reliance on intuition aligns with one of the four strategies used by Australian SAR agencies: deductive strategies, such as assessing the facts and making assumptions (Australian National Search and Rescue Council, 2023). Ensuring the ABM output is easy to comprehend and accessible will assist in the rapid decision-making processes required in a SAR situation. To assist in ensuring the use of the model output for future SAR operations, the model has been validated using real-life SAR data in consultation with SAR officers around Australia. The next step for the model is to be used in long-term lost person cases to provide new insight into these old cases. It is hoped that with continued use in less time-critical SAR operations, the model output will be trusted to be used in future time-sensitive SAR operations to assist in reducing the time taken to develop search areas, as well as determine the highest priority search areas based on human behaviour and the underlying terrain.

5. Conclusion

Through the collection and analysis of behavioural data, statistically significant similarities amongst groups of people with comparable demographics were identified, and these were used in conjunction with accurate terrain data to develop an ABM. The model included parameters specific to lost person behaviour characteristics and allowed the refinement of search areas based on the demographics of the lost person. With the inclusion of terrain data from the actual area that they are missing, the difficulty of the terrain was also taken into consideration to provide individualised results of probable search areas for a lost person. The model developed in this project can provide additional insight beyond the currently used ring model to provide more individualised results for people lost in the wilderness.

The ABM described in this paper is calibrated to the Australian context, however, it is not limited to Australian environments. Effort was made to include different environments, including woodlands, heathland and rainforest, over the four sites where data were collected. Australian search and rescue agencies note the unique demographics of Australian people and therefore, created their own database of lost person behaviour (Dacey et al., 2023). The Australian database includes incidents from the United Kingdom, the United States of America and Canada, however, it is noted that Australian lost persons behaviour is more similar to that of Canada due to our mobile and active society (Australian National Search and Rescue Council, 2023). The model uses raster data for the environment that can be customised for different environments; however, additional validation is required to assess the output of the model when applied to these environments.

Currently, the model is a prototype designed to run on a standard desktop computer or laptop. This means the area of interest that can be computed and the number of agents and model runs are limited to the specifications of the user's computer. The model was coded in R (R Core Team, 2023) to take advantage of R's ability to read data frames and avoid loops that slow the processing. However, a model run using 1000 agents is still time-consuming despite all efforts to optimise the code. This slow processing is a limitation of the model and also negatively affects its scalability. In order to scale the model to support the analysis of larger and more complex terrain, additional computational power beyond a standard computer would be required, as well as automated processes for creating rasters for environments in the area of interest, which may shift over time during a search and rescue incident.

The ABM provides evidence that can be presented on a map similar to what SAR professionals already use for search area planning and often already know. Elements they consider when designing search areas are included, however, the information from the ABM is evidence-based. The ABM is able to provide much more refined search areas based on accurate data and may also provide opportunities for further discussion around areas not thought of as likely lost person locations in strategic search area planning. The ABM has not been designed as a replacement for the ring model, however, it may be used as a tool in addition to the ring model to aid in search area refinement and support evidence-based decision-making.

Despite advances in technology and navigation, people still get lost in the wilderness. With considerable person-hours required to assist lost people, refining search areas can reduce the overall search time for a lost person. From the results of the ABM and identifying strategies to improve the uptake of spatial modelling in SAR, it is hoped that some of the findings outlined in this study can be used in the future to assist in search area planning through the reduction of search area size and ultimately support improved outcomes for people lost in the wilderness.

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