Cuckoo search algorithm for the evacuation strategy of people in flash floods using a spatiotemporal conditions weight

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Abstract. Natural disasters are responsible for the destruction of infrastructures, detrimental environmental effects as well as the loss of lives in places around the world. In particular, flash floods can be disastrous both for habitants and the environment. Flooding pollutants contaminate water and corresponding negative impacts appeared on flora, fauna and people. In addition, space in cities is becoming lesser year-by-year and rivers disappeared due to anarchic buildings in urban areas. This results in flooding as the water cannot find another route to escape other than the streets of the area. In Attica region of Greece, flooding incidents occurred after flash storms and even losses of lives have been reported. This brings up the issue of civil protection and immediate evacuation of people in case of sudden floods in populated urban areas. The first responders need to act as fast as possible to avoid losses of lives and to minimize the negative environmental impacts. In this paper, we suggest a bio-inspired algorithm based on Cuckoo Search (CS) to find the best route between hazardous places based on a weighting metric that identifies the potential danger posed by flooding. Simulation experiments were conducted to evaluate the proposed approach for improving the overall effectiveness of the evacuation procedures implemented in flood-prone areas.

1 Introduction

Floods are natural disasters that occur when water temporarily covers land that is usually dry, resulting in its inundation [1,2]. The impacts of this natural disaster are financial costs, frequency, and most importantly affect the population and socio-economic activities. Floods can be caused by various events, including heavy rainfall, river overflow, dam breakage, snow or ice melting, and even tsunamis. Rainfall-induced flooding can happen due to intense downpours over a short period or prolonged light rainfall lasting hours or even days. In Western Attica, casualties are also experienced because of a rapid flooding incident.

First responders are immediately called by the civil protection authorities of a country to intervene to places where there is risk of loss of lives in dangerous situations. Ambulances, fire departments, even community members rush to the aid of those in need [3,4]. First responders often exhibit abnormal behaviours such as traumas because of the severity of incident [5]; hence systems are essential to come to their aid to assist them in their jobs. One of these systems is the one that observes obstacles on the way and provide safe routing [6]. Sensors can come to the assistance of first rspondrs to minimise their exposure to harm. An algorithm that shows the places that are hit harder by the floods is essential. Bioinspired methods have been used to self-organise and locate a viable solution in critical cases as it can be seen in the literature [7,8,9].

We propose a novel first responder routing strategy that considers the spatiotemporal conditions of each location in relation to a flooding incident. Our approach incorporates multiple factors, including whether the area is situated on an old river, the density of buildings, and the projected precipitation within the next hour. By evaluating these factors, we assign a risk factor weight to each area, aiming to minimize the potential danger posed by flooding.

The primary objective of our routing strategy is to guide first responders in visiting crucial locations efficiently, while ensuring they evacuate these areas in a near-optimal manner to minimize the catastrophic consequences of flooding. To achieve this, we adopt a Travelling Salesman Problem (TSP) approach, where first responders need to navigate through essential evacuation sites in the most optimal sequence.

To solve the TSP problem effectively, we propose the utilization of a meta-heuristic algorithm inspired by biological behaviour called the Cuckoo Search Algorithm (CSA). This algorithm is well-suited for finding optimal or near-optimal solutions in complex optimization problems like the TSP. By applying CSA to our routing strategy, we can determine an efficient sequence of locations that first responders should visit, maximizing the effectiveness of their evacuation efforts.

In summary, our proposed first responder routing strategy incorporates a risk factor that accounts for spatiotemporal conditions related to flooding incidents. By applying a TSP approach and leveraging the Cuckoo

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Search Algorithm, we aim to guide first responders in a near-optimal manner to vital evacuation sites, minimizing the potential disastrous impacts of flooding. This strategy has the potential to enhance emergency response efforts and improve the overall effectiveness of evacuation procedures in flood-prone areas.

The remainder of this paper is organized as follows: Section 2 describes the research background and provides detailed information about the cuckoo search algorithm and the Levy Walks and Human Walks. The proposed methodology for optimising routing decisions based on the risk factor is provided and discussed in Section 3. The experimental results and the derived outcomes are presented in Section 4 and finally, in Section 5 conclusions are drawn and pointers for future research are provided.

2 Research background

2.1 Cuckoo Search Algorithm

Cuckoo Search (CS) is a nature-inspired algorithm used for optimization problems. It is inspired by the behaviour of certain cuckoo species that lay their eggs in the nests of other host birds. While some host birds detect and remove the foreign eggs or abandon their nests, certain cuckoo species have evolved to imitate the colours and patterns of the host species' eggs, increasing their chances of reproductive success. When cuckoo eggs hatch earlier than host eggs, the first cuckoo chick instinctively evicts the host eggs from the nest, ensuring a greater share of food provided by the host bird. Additionally, studies have shown that cuckoo chicks can imitate the calls of host chicks to gain more feeding opportunities. The Cuckoo Search algorithm applies these principles, utilizing randomization, host identification, and egg eviction, to effectively explore and find optimal solutions for optimization problems [10].

The Cuckoo Search (CS) algorithm, is inspired by the obligate brood parasitism seen in certain cuckoos. CS represents solutions as eggs in a nest, where cuckoo eggs represent new and potentially better solutions. The objective is to replace less optimal solutions in the nest with these new ones. Initially, each nest contains a single egg, but the algorithm can be expanded to nests with multiple eggs representing a set of solutions. CS operates based on the following key rules: each cuckoo lays only one egg at a time, randomly selecting a nest to deposit it. The best nest, containing high-quality eggs, is carried over to the next generations to preserve promising solutions.

The number of available host nests remains constant, and the presence of a cuckoo egg in a nest is discovered by the host bird with a probability denoted as Pa (Pa $\in$ (0, 1)). When discovered, the host bird can choose to discard the egg or abandon the nest and build a completely new nest.

By implementing these rules, the CS algorithm emulates the behaviour of cuckoos, employing randomization, selection of superior solutions, and replacement of suboptimal solutions. This approach enables CS to effectively search for optimal solutions in optimization problems.

To simplify the concept, the assumption that the host bird discovers a cuckoo egg can be approximated by replacing a fraction (Pa) of the total nests (n) with new nests containing random solutions. This assumption allows for a straightforward representation of fitness, where the quality or fitness of a solution is directly proportional to the objective function value.

In the original Cuckoo Search (CS), during each iteration (t), the position of each cuckoo is updated using the following movement equations:

$$x_i^{t+1} = x_i^t + \alpha L(\lambda) \qquad (1)$$

where $\alpha > 0$ is closely concerned with the problem of interests and L is the Levy flight. Typically, the parameter α in the equation remains a constant ($\alpha = O(1)$). The equation represents a stochastic equation used for random walks. Random walks are Markov chains where the next location or status depends solely on the current location (first term in the equation) and the transition probability (second term).

However, within the framework of Cuckoo Search, the random walk employed through Lévy flight is more effective for exploring the search space. The step length in Lévy flight is significantly longer in the long run compared to other methods. Lévy flight enables a random walk where the step length is drawn from a Lévy distribution, enhancing exploration capabilities in the optimization process.

$$Lu = t^{-\lambda},\ (1 < \lambda \leq 3) \qquad . \quad (2)$$

The step-length distribution of a cuckoo in Cuckoo Search (CS) follows a power-law distribution with an infinite variance and an infinite mean, resulting in a random walk process with heavy-tailed jumps. CS has been proven to be highly efficient in finding global optima. These findings have sparked further exploration of applying CS to solve complex problems like the Traveling Salesman Problem (TSP).

A significant challenge in optimizing CS for TSP is designing an effective updating scheme for the cuckoos. Finding the right strategy to update and improve the solutions within the cuckoos is a crucial aspect that demands careful attention.

2.2 Particle Swarm Optimization Algorithm

The Particle Swarm Optimization (PSO) Algorithm is a similar nature-inspired approach for searching on a multidimensional vector space [11]. It has been successfully used for the VRP by Ai and Kachitvichyanukul [12]. They proposed a decoding method and an indirect representation of two main parts to generate diverse solutions and maintain the best solution found. The first part of the representation sets priority to areas (priority list), while the second specifies the orientation of the routes (vehicles priority matrix). The latter designates each route to cover only a certain restricted region. For generating new solutions, the best-insertion policy (according to the area priority list and the vehicle priority matrix) is followed within the decoding method and a 2-opt local search is applied for improvement.

2.3 Levy Walks as Human Walks

The study in [13] demonstrates that human walks in outdoor settings covering distances less than 10 km exhibit statistically similar characteristics to Levy walks. These similarities include heavy-tail flight and pause-time distributions, as well as a pattern of super-diffusion followed by sub-diffusion, which suggests the occurrence of heavy-tail flights in confined areas. Furthermore, when combined with the findings from references [14] and [15], their results provide evidence of the scale-free nature of human mobility, extending beyond distances of a few thousand kilometres.

To support the findings, the authors constructed a simple truncated Levy-walk model. This model successfully reproduces the power-law distribution of intercontact times, which previous studies have observed in human mobility. This research highlights the resemblance between human walks in outdoor settings and Levy walks, indicating that human mobility exhibits scale-free characteristics. By employing a truncated Levy-walk model, power-law distribution of intercontact times was recreated.

3 Methodology

In this paper, we suggest a first responder routing strategy that is determined based on a risk factor that considers the spatiotemporal conditions of each place in terms of the flooding incident, comprising whether the area is built on an old river, the density of buildings and the precipitation within the next hour. The weight is given in the following equation (3),

$$w_i = G_i + 1/d_i + 1/r_i \quad (3)$$

where G_i is the area and if it is built on an old river that floods and it takes values 0 yes and 1 if it is not. Moreover, d_i is the density of buildings and it is given in number of buildings per square kilometre, as well as r_i is the precipitation of rain which is given in millimetres per hour.

The key aspect involves the determination of a weight parameter that reflects the potential risk associated with each area in relation to the risk of flooding. We assigned this weight in order to be able to identify areas where the danger of flooding is highest when the weight is minimized. This approach allows us to prioritize the evacuation of these crucial areas and minimize the catastrophic consequences of flooding events.

Our primary objective is to guide the first responders in visiting these vital locations in an optimized manner, ensuring efficient evacuation routes while minimizing the detrimental impacts of the disaster. To achieve this, we study a Travelling Salesman Problem (TSP) which entails the responders moving in a manner that efficiently covers all essential evacuation sites.

In addition, we utilize a meta-heuristic algorithm called the Cuckoo Search Algorithm (CSA). Inspired by biological processes, this algorithm offers a promising approach for solving the TSP problem efficiently. By leveraging the CSA, we can generate near-optimal routes for the first responders, ensuring they reach critical evacuation areas in the most effective manner while considering constraints such as limited resources and time sensitivity.

We can effectively address the challenges posed by the TSP problem in emergency evacuation scenarios utilizing the CSA and we can provide a practical and robust solution for guiding first responders during critical situations.

4 Experimental results

The assumption for the results is that the maximum number of building density is 200 buildings per square kilometre. Moreover, the maximum rain precipitation is 60 mm per hour. The density and the precipitation are normalised. Notably, the index of the area being built on an old river is worth more to the procedure. Initially 4 urban areas were formulated as a matrix which is inputted in the CS process. The table of the matrix is given below (Table 1).

Table 1. Areas spatiotemporal weight.

Area 1	Area 2	Area 3	Area 4
0	0.15	0.20	0.45
0.15	0	1.15	1.45
0.20	*1.15*	0	0.30
0.45	*1.45*	0.30	0

The sequence of the nests followed and the unique number of the areas followed are given in Fig. 1.

Furthermore, we take onboard the scenario of 11 areas comprising an input matrix to the implementation, each one to another associated with the respective weight. The results will comprise the areas' sequence that is passed with the algorithm. Note that the area visits show the unique areas that are being visited.

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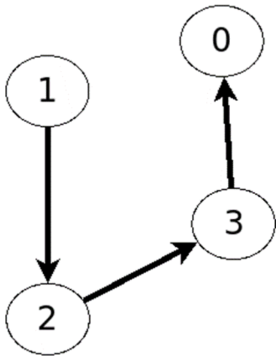

Fig. 1. Unique sequence of areas traversal.

We show the result of the modification of our algorithm and the difference with the original TSP solution with the CS. In Fig. 2 and in Fig. 3 the reader can see the difference that the algorithms produce. It is clear that the weight-based algorithm does not take under consideration the shortest path between the 11 areas.

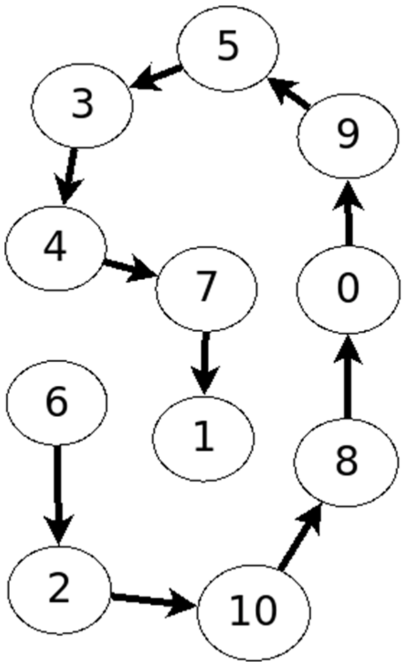

Fig. 2. Distance based routing of 11 areas.

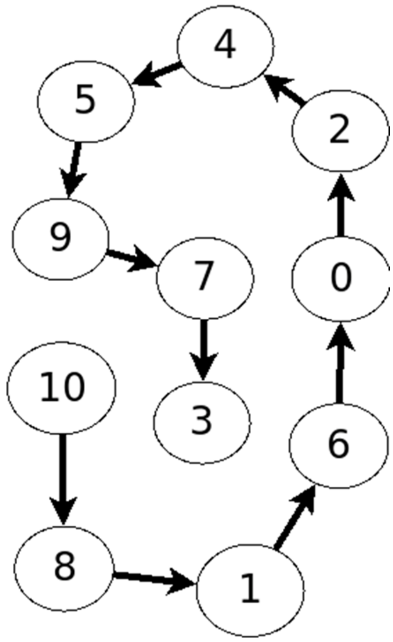

Fig. 3. Weight-based routing of 11 areas.

In an effort to demonstrate the generality and the effectiveness of the proposed method, computational experiments are also conducted using the PSO algorithm evaluating its performance in the same region in which we used the proposed methodology. The derived results reported in Fig 4 and prove the competitiveness of the CSA. Specifically, we see the cost exhibited by the CSA is quite close to the one by the PSO. In particular the CSA costs 2.05 and the PSO 2 units.

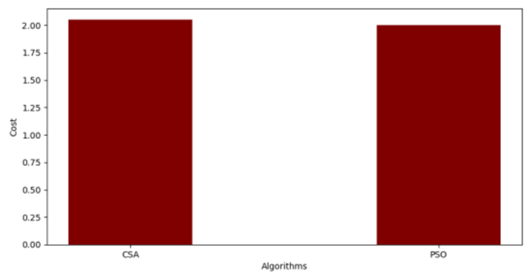

Fig. 4: Cost of CSA ans PSO

Note that the path fund by the PSO algorithm is different passing from 2, 3, 0, 1 respectivelly.

5 Conclusions

Overall, our study demonstrates the effectiveness of the CSA (Cuckoo Search Algorithm) in addressing the Traveling Salesman Problem (TSP) dealing with emerging needs. The CSA algorithm efficiently guides first responders in evacuating areas sequentially based on the assigned weight per area. The proposed approach ensures an orderly evacuation process, optimizing resource allocation and minimizing response times.

More specifically, our research reveals a noticeable disparity in distance between the conventional TSP solution and the outcome obtained through our proposed approach. The CSA algorithm exhibits superior performance, offering a more efficient and effective evacuation strategy compared to traditional methods.

To fortify our findings and provide a comprehensive analysis, future work should involve a comparative study involving other prominent algorithms such as Genetic Algorithms and Particle Swarm Optimization. Evaluating the performance and scalability of these algorithms alongside the CSA algorithm will offer a broader understanding of their respective strengths and limitations in solving the TSP problem for emergency evacuation scenarios.

By conducting such a comparative analysis, we can identify the most suitable algorithm for specific circumstances, ultimately enhancing emergency response systems and promoting public safety. Additionally, investigating the potential synergies between different algorithms may open up opportunities for hybrid approaches that combine the strengths of multiple methods, leading to even more robust and efficient solutions for the TSP problem in emergency management.

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The proposed algorithms will be used for routing in the HAIKU project.

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