Physarum-based Emergence Evacuation Plan

Hanchao Yang

University of Electronic Science and Technology of China

Yong Deng (✉ prof.deng@hotmail.com)

University of Electronic Science and Technology of China <https://orcid.org/0000-0001-9286-2123>

Danilo Pelusi

Università degli Studi di Teramo

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Abstract The rapid urbanization in many countries, especially in some developing countries keeps enlarging the size of cities and the height of buildings. However, the rise of population would also increase the risk of emergence situation that need large evacuation like fire and earth quake. While many researchers aims to build evacuation and evaluation model in different situations, some researchers tried to build a guide system for quick evacuation based on monitors and other high-tech devices. This paper severs to proposed a dependence-less evacuation plan for buildings and cities by flow guidance. Physarum algorithm and user equilibrium was adopted to estimate the optimal flux in each link, and triangular fuzz number was used to handle the uncertainty in emergence situation. Two numeric example was utilized to prove the efficiency of the proposed method.

Keywords Evacuation plan · Physarum algorithm · Fuzzy theory · User equilibrium.

Hanchao Yang

School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, 610054, China.

Yong Deng*

Institute of Fundamental and Frontier Science, University of Electronic Science and Technology of China, Chengdu, Sichuan, 610054, China. Tel(Fax):86-28-61830858

E-mail: dengentropy@uestc.edu.cn.

Danilo Pelusi

Facoltà di Scienze della Comunicazione Università degli Studi di Teramo, Teramo 64100, Italy

1 Introduction

Fire, bomb, terrorist threat and many other accidents would require the public to evacuate in a short time. Delayed and disordered evacuation would lead to a great cost of lives and heartbreaks. But in many emergence situations, electronic power, wired or wireless network is not reliable, which cause failures to monitoring, communication, and central control system that may used to build a real time crowd guide plan. Nowadays, most buildings have equipped with exit signs with independent, chargeable battery to guide people in emergence situations. The exit signs are mostly reliable because they do not need external power and Internet connection. But the shortcoming is also very obvious. In a dangerous area with multiple exits, the directions of signs are fixed and cannot change according to the situations. Hence the deployment of the exit sign is a great important which this paper tries to solve.

It is well known that modelling complex system with network is an efficient methodology [1–3]. Before this paper, there are many researchers tried to gain an insight to the evacuation and build a evacuation plan for building or city [4–6]. However some of the researchers, though built evacuation models, experiment, analysis but got no practical methods for a quick evacuations. Still, some build a evacuation system based on real-time monitoring and guide, but have no consideration of the power limit which make this system can only be used in a small area with sophisticated designed infrastructures, not for city and normal citizens. This paper makes a difference that to create a general evacuation guide plan based on optimal exit sign deployment. User equilibrium and Physarum algorithm was adopted to predict the estimate flow in each path, and fuzzy theory was used due to uncertainty. The exit signs would be allocated, at least, each intersection, and the corresponding direction was identical with the optimal flux direction.

Recently, a study has showed that a single-cell organism – Physarum – demonstrated self-adapting ability to the variation of external environments [7]. Such ability makes it be able to form highly efficient networks to connect nodes distributed at different locations with comparable performance to the actual Tokyo railway networks [8]. Since then, the research on the investigation of Physarum’s promising self-adapting ability has received increasing attention. For example, Andrew et al. [9–11] conducted numerous studies to show that Physarum is able to adapt to external environment to build highly-efficient networks to transport nutrition along the tubes.

However some of the researchers, though built evacuation models, experiment, analysis but got no practical methods for a quick evacuations. Still, some build a evacuation system based on real-time monitoring and guide, but have no consideration of the power limit which make this system can only be used in a small area with sophisticated designed infrastructures, not for city and normal citizens. This paper makes a difference that to create a general evacuation guide plan based on optimal exit sign deployment. User equilibrium and Physarum algorithm was adopted to predict the estimate flow in each path, and fuzzy theory was used due to uncertainty. The exit signs would

be allocated, at least, each intersection, and the corresponding direction was identical with the optimal flux direction.

The following section was arranged as follows. The second section is preliminaries that serves to introduce the the adopt algorithm including Physarum Algorithm, fuzzy theory, and user equilibrium. The Third section is proposed method for explaining how user equilibrium and fuzzy theory was used in Physarum algorithm, and how this method works for evacuation plan. The fourth section would be numeric examples contains two example about city and buildings. Finally, the fifth section would draw a conclusion and prospection of this paper.

2 Preliminaries

In this section, preliminaries about Physarum algorithm, user equilibrium and triangular fuzzy number would be introduced for a better understanding towards the proposed method.

2.1 Physarum algorithm

Physarum indicates Physarum polycephalum which is one kind in slime mold with network-structured body and excellent network optimal capacity [12]. In 2007, Nakagaki et al [13] have conducted a bionic experiment and proved Physarum polycephalum could find the shortest path in a artificial maze on a agar plate. After that many other researchers proved its network optimizing and design capacity [14–16]. In 2010, Tero et al build a *Physarum algorithm* [8] based on the bionic experiment and solved the shortest path problem raised by Nakagaki in citation [13]. The idea of Physarum polycephalum is simple that the protoplasm tube carrying nutritions would thicken, while others would shrivel. The Physarum algorithm adopted this idea and build a adaptive function to update the conductivity in each path after the corresponding flux was calculated.

Physarum algorithm have show a great ability in graph theory [17], in shortest path problem [18] at the beginning and network design [10, 19, 20] as well as the following traffic network optimizing [19, 21]. Network modelling complex system is an open issue [22–25]. Physarum algorithm also prove its adaptivity in uncertainty network [26]. In this paper, Physarum algorithm was utilized to calculate the optimal flux in each path.

In Physarum algorithm, the proposed area is usually illustrated as a graph or network noted as $G(V, E)$. G indicates the whole network while V and E represents the set of vertexes and edges in this network and V_i and $E_{i,j}$ indicates vertex i and edge connected vertexes i and j respectively. According to Ref. [8], the source and sink vertexes are particularly denoted as V_1 and V_2 , and the remaining vertexes are marked as V_3, V_4, V_5 , etc. Besides, every vertex was assigned with pressure attribute p , and in edges, the flux attribute

was defined as Q . According to Poiseuille equation [27], the flow in each edges can be calculated as follows:

$$Q_{ij} = \frac{\pi r_{ij}^4}{8\eta L_{ij}}(p_i - p_j) \quad (1)$$

Where η represents the viscosity of the fluid, r is the radius of the tube, and p_i , $L_{i,j}$ indicates pressure in vertex i and edge length of $E_{i,j}$. Normally, conductivity would be defined as D to replace $\pi r_{ij}^4/8\eta$, equation 1 can be rewritten as:

$$Q_{ij} = \frac{D_{ij}}{L_{ij}}(p_i - p_j) \quad (2)$$

Then based on the conservation law of flux, the inflow and outflow of every node must be balanced which acts the same as Kirchhoff's law. While the source and the sink vertexes are different which provided the net-outflow and net-inflow for the network. Hence the equation could be derived as follows:

$$\sum_i Q_{ij} = \begin{cases} -1 & \text{for } j = 1, \\ +1 & \text{for } j = 2, \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

In Eq. 3, the net flow of source and sink node was set as 1. Replace Q_{ij} with $D_{i,j}$ by Eq. 2 could obtain the equation used for pressure calculation as follows:

$$\sum_i \frac{D_{ij}}{L_{ij}}(p_i - p_j) = \begin{cases} -1 & \text{for } j = 1, \\ +1 & \text{for } j = 2, \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

The Physarum polycephalum would expand itself for search for food, correspondingly, the Physarum algorithm would initialize the conductivity in each edge to ensure the connection with source and sink nodes. The initial value varies from different applications. In most situations, the link weights L is known, so, by solving Eq. 4, the $p_i - p_j$ will be clear. Normally, p_n was set to zero to be the reference pressure for all nodes. n is the index of the least node.

The flux attribute could be computed base on the value of L , D and p as Eq. 2. In Ref. [8], the adaptive function was designed as Eq. 5 to ensure the conductivity evolves with the flux.

$$\frac{d}{dt}D_{ij} = f(|Q_{ij}|) - D_{ij} \quad (5)$$

Eq. 5 illustrate that conductivity D changes with the flow Q in the same direction. The option of function $f(|Q_{ij}|)$ would influence the convergent efficiency of Physarum algorithm in different applications. But it does not matter much and for simplicity, $f(|Q_{ij}|)$ was always set as $|Q_{i,j}|$. In the algorithm, the continued form, as the equation 5 shown, would be reformed in discrete as following:

$$\frac{D_{ij}^{n+1} - D_{ij}^n}{\Delta t} = |Q| - D_{ij}^{n+1} \quad (6)$$

From the above, the original Physarum algorithm could be written as Algorithm:

Algorithm 1 The original Physarum

Input: L , $source$, $sink$

Output: D

Initialize D , D_{temp} I

while $\sum |D - D_{temp}| < \epsilon$ **do**

$D_{temp} = D$

 Solve P via Eq.4

 Calculate Q with Eq.2

 Update D by Eq. 6

end while

In the pseudo-code, ϵ is a minimum value that indicate the convergence of conductivity. Where I is the vector contains net flow of all nodes.

2.2 User equilibrium

In 1952, Wardrop et al [28] proposed the basic principle of user equilibrium: 'Any travels cannot decrease themselves cost by changing travel route when the traffic system is equilibrium.' The equilibrium status was subjected to the capacity of paths in the network system. Even if all travelers choose the current fastest route, due to the limitation of capacity, time spent on paths would increase and the routes from one point to another would cost the same time, which called equilibrium status. In this paper, the user equilibrium, accompanied with physarum algorithm, are used to find the optimal flux in each link with the constrains of link capacity.

Denote c_0^a , c^a , x^a and u^a as the free flow cost, flow cost, flux and the capacity in link a , $a \in E$. Define $P_{(o,d)}$ as the set of routes from origin point o to destination point d . For a particular path p , $p \in P$, the traffic flow can be denoted as $f_{(o,d)}^p$, and the cost of p is $c_{(o,d)}^p$.

In 1956, Beckmann et al [29] build a flow-cost formula based on Wardrop's principle:

$$\mu_{(o,d)} - c_{(o,d)}^P = \begin{cases} = 0, & f_{(o,d)}^p > 0, \forall p \in P_{(o,d)}, \forall (o,d) \in \Pi \\ \leq 0, & f_{(o,d)}^p = 0, \forall p \in P_{(o,d)}, \forall (o,d) \in \Pi \end{cases} \quad (7)$$

Where Π is the set of $O - D$ pairs pairs and $\mu_{(o,d)}$ id the minimum cost for path p in the user equilibrium status. Flow would cause congestion in links and increase the travel time which was denoted as follows:

$$c^a = c^a(x^a, u^a, c_0^a) \quad (8)$$

The cost function c^a defined varies for different applications but always give a significant punishment to overload flow. In this way, the user equilibrium model can be made as the:

$$\min Z(w) = \sum_{a \in E} \int_o^{x^a} c^a(w) dw \quad (9)$$

$$s.t. \begin{cases} \sum_{p \in P} f_{(o,d)} = q(o,d) \forall (o,d) \in \Pi \\ x^a = \sum_{(o,d) \in \Pi} \sum_{p \in P_{(o,d)}} f_{(o,d)}^p \delta_{(o,d)}^{p,a} \forall a \in E \\ f_{(o,d)}^p \geq 0 \end{cases} \quad (10)$$

The δ was defined as Eq. 11:

$$\delta_{(o,d)}^{p,a} = \begin{cases} 1, a \in p, \\ 0, a \notin p, \end{cases} \forall a \in E, \forall p \in P_{(o,d)} \quad (11)$$

Smith et al [30] proved there exist one unique solution for Eq. 9. In this paper, the Physarum algorithm was used to solve the the optimizing problem as Eqs. 9 and 10.

2.3 Fuzzy set and triangular fuzzy number

The real application is very complex with many uncertain factors [31, 32]. Many mathematical tools was created to model the uncertainty in the physical world [33, 34], such as probability [35, 36], random permutation set [37], evidence theory [38, 39] and entropy function [40–42]. Among those tools, fuzzy theory, proposed by Zadeh in 1965 [43] are well developed and widely used in the near decades [44–46]. The triangular fuzzy number [47] is a simple and easily-used fuzzy set system and have been applied to many applications.

Triangular fuzzy number was introduced by Hanss et al at reference [48]. Denote a fuzzy set as $\tilde{A}$ on a universe set X , which could be expressed as follows:

$$\tilde{A} = \{ \langle x, \mu_{\tilde{A}}(x) \rangle \mid x \in X \} \quad (12)$$

In Eq. 12, $\mu_{\tilde{A}}(x)$ is the membership function of $\tilde{A}$ servers to illustrate the degree of membership of x in A . The definition of fuzzy set differs from different applications, but a random fuzzy set is hard to put into practice to compute. A linear membership function introduce by reference [48] was widely used, call triangular fuzzy number. The membership function can be expressed as:

$$\mu_{\tilde{A}} = \begin{cases} 0, & x \leq a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}, & a_2 \leq x \leq a_3 \\ 0, & a_3 \leq x \end{cases} \quad (13)$$

As illustrated in Eq. 13, there are three key parameters to denote a triangular fuzzy set which can be presented as a triplet: (a_1, a_2, a_3) . The membership function was plotted as a triangular as Fig. 1 shown.

Fig. 1: Membership function of triangular fuzzy number

Giachetti et al [49] introduced arithmetic for triangular fuzzy number as follows:

$$\begin{aligned}
 \tilde{A} \oplus \tilde{B} &= (a_1 + a_1, a_2 + b_2, a_3 + b_3), \text{ for addition} \\
 \tilde{A} \ominus \tilde{B} &= (a_1 - a_1, a_2 - b_2, a_3 - b_3), \text{ for subtraction} \\
 \tilde{A} \otimes \tilde{B} &= (a_1 \times a_1, a_2 \times b_2, a_3 \times b_3), \text{ for multiplication} \\
 \tilde{A} \oslash \tilde{B} &= (a_1 / a_1, a_2 / b_2, a_3 / b_3), \text{ for division}
 \end{aligned} \tag{14}$$

As Eq. 14 presents, it is easily to conduct arithmetic on triangular fuzzy number which was adopted in the proposed method of this paper. Besides, it is also important to compute the crisp number from a fuzzy number. Hassan-zadeh et al [50] introduce another method to transfer fuzzy to crisp as Eq. 16.

$$P(\tilde{A}) = \frac{1}{6}(a_1 + 4 \times a_2 + a_3) \tag{15}$$

$$P(\tilde{A}) = \sqrt{\frac{1}{2} \sum_{i=1}^n (a_1^i)^2 + \frac{1}{2} \sum_{i=1}^n (a_3^i)^2} \tag{16}$$

Considering the difficulty of the parameter estimation, this paper adopted Deng's method to compute the crisp pressure P to determine the flow direction, for better application in simulation and practice.

3 Proposed Method

In this paper, the detail of the proposed algorithm would be introduced including the modified Physarum algorithm for evacuation optimizing, user equilibrium principle and equations for updating edge cost, and applying fuzzy number in Physarum algorithm.

In the original Physarum algorithm, only one OD pairs was set, but in practical emergence situations, the exit port would be more than one. There are quite lot attempts in a single-source multi-sink Physarum algorithm [51], however all of those algorithms requires a preset outlet flow in each exit port. But in the evacuation, the amount of people evacuated from each evacuation point is not a determined number. Therefore the conventional single-source multi-sink method is not suitable for the evacuation model. To solve this problem, we add one external node out of the evacuation network as the final exit point connected all outlets. Denote this node as e , and the set of exit point as V_e , the new network $G'(V', E')$ can be build as Eq. 17.

$$\begin{aligned} V' &= V \cup \{e\} \\ E' &= E \cup \{E(e, i), \forall i \in V_e\} \end{aligned} \quad (17)$$

Besides the outlets, the points contained people and required evacuation are also a big number. Since the exit points are drawn to one, the problem was turn to one-sink multi-source problem which is the inverse of one-source multi-sinks problem and could be easily solved. Denote the set resident points as V_r , the Eq. 3 can be rewrite as Eq. 18.

$$\sum_i Q'_{ij} = \begin{cases} -f_j & \text{for } j \in V_r, \\ +\sum_j f_j & \text{for } j = e, \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

Where the f_j in the population in each resident point, and $\sum_j f_j$ is the total amount of people that the external point would receive. Replace the Eq. 3 with Eq. 18 can get the modified Physarum algorithm, however it need to work with user equilibrium. The update of edge cost would follow the update of the edge conductivity after every iteration. Consider time t as the key attributes considered in evacuation, the update function can be expressed as:

$$L_{i,j}^{n+1} = \frac{L_{i,j}^n + t_a(Q_{i,j}^{n+1})}{2} \quad (19)$$

In Eq. 19, $L_{i,j}^{n+1}$ and $Q_{i,j}^{n+1}$ are the edge cost and edge flux in $n+1$ -th iteration. Refer to UE principles, the actually Edge cost is $L_{i,j}^0 + t_a(Q_{i,j}^{n+1})$, but dramatic change is dangerous for algorithm stability. That is why the adaptive rate was adopted as $1/2$. As for the time cost function $t_a(Q)$, the Bureau of Public Road function [52] is usually selected:

$$t_a = \alpha_a(1 + B(\frac{Q_{i,j}}{c_{i,j}})^q) \quad (20)$$

Where α_a is the free travel time and $c_{i,j}$ is the capacity of link $E_{i,j}$. B and q are parameters which depends on the applications. In this way, the original Physarum algorithm can be modified as Alg. 2.

Note that, precisely quantize the network model for evacuation is not easy, hence we introduced fuzzy theory to this algorithm. Firstly, the edge cost should be fuzzy up : $L_{i,j} - > \tilde{L}_{ij}, \forall i, j \in V$. Like other triangular fuzzy number,

Algorithm 2 Modified Physarum with User Equilibrium

Input: L, V_e
Output: D
Initialize D, D_{temp}, I
Build L' based on Eq. 17
while $\sum |D - D_{temp}| < \epsilon$ **do**
 $D_{temp} = D$
 Solve P via Eq.18
 Calculate Q with Eq.2
 Update D by Eq. 6
 Update L' by Eq. 19
end while

$\tilde{L}_{i,j}$ could be expressed as a triplet: $(L_{i,j}^l, L_{i,j}, L_{i,j}^u)$. $L_{i,j}^l$ and $L_{i,j}^u$ is the lower and upper limit of the fuzzy number. In this way, the equation 4 can be rewrite as:

$$\begin{aligned} \sum_i \frac{D_{ij}}{L_{ij}^u} (p_i^l - p_j^l) &= \begin{cases} -1 & \text{for } j = 1, \\ +1 & \text{for } j = 2, \\ 0 & \text{otherwise} \end{cases} \\ \sum_i \frac{D_{ij}}{L_{ij}} (p_i - p_j) &= \begin{cases} -1 & \text{for } j = 1, \\ +1 & \text{for } j = 2, \\ 0 & \text{otherwise} \end{cases} \\ \sum_i \frac{D_{ij}}{L_{ij}^l} (p_i^u - p_j^u) &= \begin{cases} -1 & \text{for } j = 1, \\ +1 & \text{for } j = 2, \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (21)$$

In Eq. 21, pressure P was also fuzzy up to be $\tilde{P}(p^l, p, p^u)$. In this way, the $\tilde{P}$ could be solved from the three independent equations. The pressure is used to calculated flow Q . In the fuzzy condition, the equation 2 was modified as follows:

$$Q_{i,j} = D_{i,j} \times Dis\left(\frac{\tilde{p}_i}{\tilde{L}_{i,j}}, \frac{\tilde{p}_j}{\tilde{L}_{i,j}}\right) \quad (22)$$

How to determine the distance function in real application is still an open issue [53]. The distance function in Eq. 22 was proposed by Gildeh and Gien in 2001 [54], for triangular fuzzy number, the expression is:

$$Dis(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{6} \left[\sum_{i=1}^3 (b_i - a_i)^2 + (b_2 - a_2)^2 + \sum_{i \in \{1,2\}} (b_i - a_i)(b_{i+1} - a_{i+1}) \right]} \quad (23)$$

In this way, the flow attribute in the algorithm is a accuracy value, so the adaptive function for updating edge conductivity can keep no change. In all, the fuzzy Physarum algorithm with user equilibrium can be illustrated by algorithm 3.

Algorithm 3 Fuzzy Physarum Algorithm with User Equilibrium

Input: L, V_e, B, q **Output:** P Initialize D, D_{temp}, I Build L' based on Eq. 17**while** $\sum |D - D_{temp}| < \epsilon$ **do** $D_{temp} = D$ Solve P via Eq.21 Calculate Q with Eq.22 and Eq. 23 Update D by Eq. 6 Update L' by Eq. 19**end while**

Noted that the output changed from D to P , which is because conductivity can not be the index for flow direction, which flow Q was calculated in positive due to $Dis()$ function in Eq. 23. Hence the pressure was output to computer the relative pressure in edges and calculate the flow direction.

4 Numeric Examples

In this section, two examples would be put into test to shown the efficiency of the proposed method. The first one we choose the Louver to example a tourist building. We model the network topology based on its plan view, and estimate the population based on area. The second one we choose Chicago to example a big city in emergency evacuation of nature disasters. The network topology was taken from an open source dataset, since the downtown area denser points, we assume the every resident point have the same amount of people. Then we made a Matlab simulation for the proposed Physarum algorithm and simulate the evacuation flow in the two examples.

Firstly, emergence situation in buildings is considered like fire accident and boom attack. Louvre is chosen to be the test object which serves for millions of tourist per year. The Louvre was a building with five floor (two underground and three on ground) and five outlets. In view of visible visualization, this paper took the ground floor to be the example which connects with four outlets directly.

As the Fig. 2 shown, the four outlets connected with the ground floor are Carrousel Entrance, Passage Richelieu, Porte des Art and Porte des Lions, which in red front in the figure. Noted that though Pyramide is also on the ground, but it did not connect with the main building.

In the Louvre, space and exhibitions are continuous and so we designed a simple way to determine the population density and build the network. Firstly, the main building was partition into two parts based on the exhibition deployment which mark in blue at the Fig. 3a, Besides, the two partitions was divided into several zones to build the network model as the Fig. 3b. As the figure illustrated, the zones are relatively small because the two near zone may flow to different direction when near the watershed.

Fig. 2: The plan view of the Louvre

Fig. 3: Data initialize for Louver

In the sparse partition, the population density was denoted as 1 unit, and the crowd partition was denoted as 3 units. The population in each zone is calculated as the product of area and the population density. The capacity was in direct proportion to the width of the connector. Noted in Eq. 20, parameter B and α is required. In the two examples, the value was set to 0.15 and 4. The result of the the proposed method in Louver first floor was shown in Fig. 4

As figure. 4 shown, people flow to the nearest outlets in most zones. As it had been though, there are seven diverse points marked by red circles. In this way, in most zones exit sign should be placed in one direction, in seven zones the direction should be singed in two or three direction and the people shall decide the which to follow based on the real situation.

Apart from building evacuation, the city evacuation was also been test which may help in nature disasters or terrorist attacks. In this example Chicago was selected and the data was from *Transportation Networks for Research* at <https://github.com/bstabler/TransportationNetworks>. This data set contains nodes, coordinates, links and corresponding capacities which represented as Fig.5

Fig. 4: The optimal flow direction by the proposed method

Fig. 5: The Chicago city network

As the figure shown, the population node is in red, the roads are in blue and the outlets in margin are marked by red *. Consider the all nodes are the resident points and assume only every resident node contains one unit of population. Noted there are some wired connection in the south-east of the Chicago map. Which seems like a data mistake, but it's I-57 highway presented in straight line.

In the dataset, the capacity in each link ranges from 49500 to 500, with the consideration of 933 nodes exists, the capacities were minus 100 times to $495 - 5$. By applying the proposed method in Chicago network, the final

result could be viewed at Fig. 6a. There are three outlets were isolated in the south-east due to the wired connection in the dataset.

Fig. 6: The result of the proposed method in Chicago city network

Take the north-west part as an example which presented at Fig. 6b. It is clear that there are distinct evacuation area for each outlets, which was denoted by red lines. Besides, as the example in the Louver, there are still diverse point exit as the red circle shows. The two example illustrated the proposed method could make a reasonable result for exit sign deployment.

The simulation and visualization code is available at <https://github.com/hcyang22/Physarum-evacuation>.

5 Conclusion

In this paper, a general evacuation guide method was proposed by optimizing the deployment of exit signs via modified Physarum algorithm, fuzzy theory and user equilibrium. Physarum algorithm servers to find the globe optimizing evacuation flow, and the fuzzy theory helps to model the uncertainty in the physical world. The contribution of this paper can be summarized as follows:

- Exit sign with independent battery is a stable guide for evacuation, and this paper provides a novel allocation method which few had paid attention on.
- User equilibrium and fuzzy theory was adopt to illustrate the crowdedness and uncertainty in evacuation.

Compare to other evacuation schemes, the advantage of the proposed method is it provided a numeric design method, with consideration of path capacity and physical uncertainty. However, there are some drawbacks, the proposed method don't use Equ.16 for more accurate uncertainty measurement, which is a trade of the the modeling difficult. And the proposed method only model the population uncertainty, not include the network topology, since in emergency situation, some links or vertices may not available for human to travel through.

In the future, the authors planned to consider the dangerous point like gas-leak and landslides. Besides it is a pity to not fuzzy up all the values in the whole iterations, though the authors attempted and found mis-convergence. But the authors still believe the entire fuzzy up would be better to model the uncertainty and continue the research.

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Compliance with Ethical Standards

Conflict of interest The authors declare they have no conflict of interest.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Y. Wu, B. Kang, H. Wu, Strategies of attack–defense game for wireless sensor networks considering the effect of confidence level in fuzzy environment, *Engineering Applications of Artificial Intelligence* 102 (2021) 104238.
2. H. Wang, Y. P. Fang, E. Zio, Risk assessment of an electrical power system considering the influence of traffic congestion on a hypothetical scenario of electrified transportation system in new york state, *IEEE Transactions on Intelligent Transportation Systems* 22 (2021) 142–155.
3. H. Wang, A. F. Abdin, Y.-P. Fang, E. Zio, Resilience assessment of electrified road networks subject to charging station failures, *Computer-Aided Civil and Infrastructure Engineering* (2021).
4. S. A. Bagloee, K. H. Johansson, M. Asadi, A hybrid machine-learning and optimization method for contraflow design in post-disaster cases and traffic management scenarios, *Expert Systems with Applications* 124 (2019) 67–81.
5. P. Ghasemi, K. Khalili-Damghani, A. Hafezolkotob, S. Raissi, Uncertain multi-objective multi-commodity multi-period multi-vehicle location-allocation model for earthquake evacuation planning, *Applied Mathematics and Computation* 350 (2019) 105–132.

6. J. A. Munoz, V. Calero, I. Marin, P. Chavez, R. Perez, Adaptive evacuation management system based on monitoring techniques, *IEEE Latin America Transactions* 13 (2015) 3621–3626.
7. C. Gao, C. Liu, D. Schenz, X. Li, Z. Zhang, M. Jusup, Z. Wang, M. Beekman, T. Nakagaki, Does being multi-headed make you better at solving problems? a survey of physarum-based models and computations, *Physics of life reviews* 29 (2019) 1–26.
8. A. Tero, S. Takagi, T. Saigusa, K. Ito, D. P. Bebber, M. D. Fricker, K. Yumiki, R. Kobayashi, T. Nakagaki, Rules for biologically inspired adaptive network design, *Science* 327 (2010) 439–442.
9. A. Adamatzky, J. Jones, Road planning with slime mould: if physarum built motorways it would route m6/m74 through newcastle, *International Journal of Bifurcation and Chaos* 20 (2010) 3065–3084.
10. A. Adamatzky, O. Allard, J. Jones, R. Armstrong, Evaluation of french motorway network in relation to slime mould transport networks, *Environment and Planning B* 12 (2017) 1–11.
11. M.-A. I. Tsompanas, G. C. Sirakoulis, A. I. Adamatzky, Evolving transport networks with cellular automata models inspired by slime mould, *IEEE Transactions on Cybernetics* 45 (2015) 1887–1899.
12. C. Gao, S. Chen, X. Li, J. Huang, Z. Zhang, A physarum-inspired optimization algorithm for load-shedding problem, *Applied Soft Computing* 61 (2017) 239–255.
13. T. U. e. a. T. Nakagaki, M. Iima, Minimum-risk path finding by an adaptive amoebal network, *Physical Review Letters* 99 (2007).
14. A. Adamatzky, *Physarum machines: computers from slime mould*, volume 74, World Scientific, 2010.
15. M. Liang, C. Gao, Z. Zhang, A new genetic algorithm based on modified physarum network model for bandwidth-delay constrained least-cost multicast routing, *Natural computing* 16 (2017) 85–98.
16. A. Adamatzky, Developing proximity graphs by physarum polycephalum: does the plasmodium follow the toussaint hierarchy?, *Parallel Processing Letters* 19 (2009) 105–127.
17. C. Gao, M. Liang, X. Li, Z. Zhang, Z. Wang, Z. Zhou, Network community detection based on the *physarum*-inspired computational framework, *IEEE/ACM Transactions on Computational Biology and Bioinformatics* 15 (2018) 1916–1928.
18. Y. Liu, C. Gao, Z. Zhang, Y. Lu, S. Chen, M. Liang, L. Tao, Solving np-hard problems with physarum-based ant colony system, *IEEE/ACM transactions on computational biology and bioinformatics* 14 (2015) 108–120.
19. D. T. Schenz, Y. Shima, S. Kuroda, T. Nakagaki, K. Ueda, A mathematical model for adaptive vein formation during exploratory migration of physarum polycephalum: Routing while scouting, *Journal of Physics D Applied Physics* (2017).
20. H. Yang, Y. Deng, J. Jones, Network division method based on cellular growth and physarum-inspired network adaptation., *International Journal*

- of Unconventional Computing 13 (2018).
21. X. Zhang, S. Mahadevan, A bio-inspired approach to traffic network equilibrium assignment problem, *IEEE Transactions on Cybernetics* doi: 10.1109/TCYB.2017.2691666 (2017).
 22. T. Wen, K. H. Cheong, The fractal dimension of complex networks: A review, *Information Fusion* 73 (2021) 87–102.
 23. L. Chen, Y. Deng, K. H. Cheong, Probability transformation of mass function: A weighted network method based on the ordered visibility graph, *Engineering Applications of Artificial Intelligence* 105 (2021) 104438.
 24. X. Song, F. Xiao, Combining time-series evidence: A complex network model based on a visibility graph and belief entropy, *Applied Intelligence* (2022) DOI: 10.1007/s10489-021-02956-5.
 25. L. Xiong, X. Su, H. Qian, Conflicting evidence combination from the perspective of networks, *Information Sciences* 580 (2021) 408–418.
 26. M. Zhang, R. Zheng, Q. Wu, W. Wei, X. Bai, H. Zhao, B-iTRS: A Bio-Inspired Trusted Routing Scheme for Wireless Sensor Networks, *Journal of Sensors* (2015).
 27. H. S. Badeer, C. E. Synolakis, The bernoulli-poiseuille equation, *The Physics Teacher* 27 (1989) 598–601.
 28. J. G. Wardrop, Road paper. some theoretical aspects of road traffic research., *Proceedings of the institution of civil engineers* 1 (1952) 325–362.
 29. M. Beckmann, C. B. McGuire, C. B. Winsten, *Studies in the Economics of Transportation*, Technical Report, 1956.
 30. M. J. Smith, The existence, uniqueness and stability of traffic equilibria, *Transportation Research Part B: Methodological* 13 (1979) 295–304.
 31. T. Wen, J. Cao, K. H. Cheong, Gravity-based community vulnerability evaluation model in social networks: Gbcve, *IEEE Transactions on Cybernetics* (2021) 10.1109/TCYB.2021.3123081.
 32. X. Gao, X. Su, H. Qian, X. Pan, Dependence assessment in Human Reliability Analysis under uncertain and dynamic situations, *Nuclear Engineering and Technology* (2021) <https://doi.org/10.1016/j.net.2021.09.045>.
 33. L. A. Zadeh, Preliminary draft notes on a similarity-based analysis of time-series with applications to prediction, decision and diagnostics, *International Journal of Intelligent Systems* 34 (2019) 107–113.
 34. L. Chen, Y. Deng, An improved evidential Markov decision making model, *Applied Intelligence* (2021) 10.1007/s10489-021-02850-0.
 35. C. Huang, X. Mi, B. Kang, Basic probability assignment to probability distribution function based on the shapley value approach, *International Journal of Intelligent Systems* 36 (2021) 4210–4236.
 36. Q. Wu, Y. Deng, N. Xiong, Exponential negation of a probability distribution, *Soft Computing* (2021) 10.1007/s00500-021-06658-5.
 37. Y. Deng, Random permutation set, *International Journal of Computers Communications & Control* 17 (2022) 4542.
 38. F. Xiao, A distance measure for intuitionistic fuzzy sets and its application to pattern classification problems, *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 51 (2021) 3980–3992.

39. D. Xie, F. Xiao, W. Pedrycz, Information quality for intuitionistic fuzzy values with its application in decision making, *Engineering Applications of Artificial Intelligence* (2021) DOI: 10.1016/j.engappai.2021.104568.
40. Y. Song, Y. Deng, Entropic explanation of power set, *International Journal of Computers Communications & Control* 16 (2021) 4413.
41. H. Cui, L. Zhou, Y. Li, B. Kang, Belief entropy-of-entropy and its application in the cardiac interbeat interval time series analysis, *Chaos, Solitons & Fractals* 155 (2022) 111736.
42. Q. Zhou, Y. Deng, Belief extropy: Measure uncertainty from negation, *Communications in Statistics - Theory and Methods* (2021) DOI: 10.1080/03610926.2021.1980049.
43. L. A. Zadeh, Fuzzy sets, *Information and control* 8 (1965) 338–353.
44. I. Dzitac, F. G. Filip, M.-J. Manolescu, Fuzzy logic is not fuzzy: World-renowned computer scientist lotfi a. zadeh, *International Journal of Computers Communications & Control* 12 (2017) 748–789.
45. T. Wang, X. Wei, J. Wang, T. Huang, H. Peng, X. Song, L. Valencia-Cabrera, M. J. Pejrez-Jimenez, A weighted corrective fuzzy reasoning spiking neural p system for fault diagnosis in power systems with variable topologies, *Engineering Applications of Artificial Intelligence* 92 (2020).
46. F. Xiao, CaFtR: A fuzzy complex event processing method, *International Journal of Fuzzy Systems* (2021) DOI: 10.1007/s40815-021-01118-6.
47. S.-M. Chen, Fuzzy system reliability analysis using fuzzy number arithmetic operations, *Fuzzy sets and systems* 64 (1994) 31–38.
48. M. Hanss, *Applied fuzzy arithmetic*, Springer, 2005.
49. R. E. Giachetti, R. E. Young, A parametric representation of fuzzy numbers and their arithmetic operators, *Fuzzy sets and systems* 91 (1997) 185–202.
50. R. Hassanzadeh, I. Mahdavi, N. Mahdavi-Amiri, A. Tajdin, A genetic algorithm for solving fuzzy shortest path problems with mixed fuzzy arc lengths, *Mathematical and Computer Modelling* 57 (2013) 84–99.
51. Y. Sun, S. Halgamuge, Fast algorithms inspired by physarum polycephalum for node weighted steiner tree problem with multiple terminals, in: *Evolutionary Computation*.
52. O. P. R. BUREAU, *Traffic assignment manual*, US Department of Commerce (1964).
53. C. Cheng, F. Xiao, A distance for belief functions of orderable set, *Pattern Recognition Letters* 145 (2021) 165–170.
54. B. Sadeghpour-Gildeh, D. Gien, The distance and the coefficient of correlation between two random variables, in: *Proceedings of the French Meeting on Fuzzy Logic and Its Applications*, volume 1, pp. 97–102.