A Graph-Based Approach for Applying Biologically-Inspired Slime Mold Algorithms for Repairing a Power Transmission Network after an Electromagnetic Pulse Attack

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***Abstract*—This paper presents a novel approach based on a simulated slime mold algorithm to elaborate a repair plan for a power transmission network after an EMP attack. The algorithm is applied to a graph model to identify the most critical areas to be repaired, corresponding to the slime mold's nourishing network established between food sources. The open-source SISMO (Simulation of Slime Molds) algorithm was adapted for this network planning task and was fed with the positions of relevant power plants and substations of the Carinthian power transmission network. However, the initial results were unsatisfying as they often contained disconnected networks or introduced new, non-existent connections. To address this problem, we propose the use of graph visualization algorithms, such as the Force Atlas, Force Atlas2, and Yifan-Hu Proportional, to improve the layout based on existing network connections. Overall, the paper provides valuable insights into the potential applications of bio-inspired algorithms, such as the slime mold simulation in solving network planning tasks and the use of graph visualization algorithms for preprocessing map-based graphs to be used in bio-inspired spatial algorithms.**

***Index Terms*—Slime Mold Algorithm, Bio-inspired Algorithms, Network planning, Power transmission restoration**

I. Introduction

Electricity is an essential aspect of modern life, powering nearly every aspect of daily activities, including critical national infrastructure. Thus, the loss of electricity can have serious consequences, leading to economic impact and severe medical problems. Therefore, the ability to restore electricity is critical, especially after a catastrophic event. In this paper we investigate the hypothetical situation of a damaged electricity grid after an electromagnetic pulse (EMP) attack. In such an event, all unprotected electronics collapse and transmission networks fail, seriously hampering the restoration process. However, cables and overland wires stay in place, which means that repair should follow the previously existing network structure. Given the importance of the electricity grid service, the repair of the network should be performed as quick as possible, with establishing connections between neuralgic points first. To address this challenge, Daniel Himmelstein [1] proposed a novel approach that uses slime molds to design efforts to rebuild the power grid after an EMP attack. Unlike traditional human planning approaches, using slime molds as the architect for network design offers several advantages, especially given the impact of an electromagnetic attack. Slime molds can identify the locations that need to be repaired, resulting in a semi-functional network again.

This paper builds on Himmelstein's proposal by presenting a graph-based approach to apply biologically inspired slime mold algorithms to repair a power transmission network after an electromagnetic pulse attack. The proposed approach uses a graph model to represent the power transmission network, with nodes representing substations and edges representing transmission lines. A simulated slime mold algorithm is then applied to the graph model to identify the most critical areas to be repaired, resulting in a fast restoration process. The significance of the paper is that it represents a novel approach of a repair strategy of a power transmission after an EMP attack that potentially can significantly reduce the time and resources required to restore critical infrastructure.

The aim of this paper is to evaluate a simulated slime mold algorithm for generating a repaired power transmission network. In addition, the effectiveness of layout algorithms in improving simulation results over using geographic network maps are investigated. By utilizing graph layout algorithms, we can construct a new representation of the power grid, leading to a more efficient reconstruction plan. Ultimately, our goal is to develop a reliable and efficient approach to rebuilding the power grid in the aftermath of an EMP attack to ensure the protection of national security, medical care, and the economy.

The remaining parts of the paper are structured as follows: SectionII discusses related work and provides a comparison to the presented approach. Section III describes our implementation of a simulated slime mold algorithm and the necessary adaptations to fit it to the specified problem. Section IV introduces the selected layout algorithms used in this work. Section V presents simulation results for different settings using the simulated slime mold approach on the specified problem. Section VI assesses and discusses the results. Section VII concludes the paper and gives an outlook to possible future work.

II. Related Work

There has been limited research on the applications of slime molds and bio-inspired algorithms in energy networks. Besides Himmelstein's suggestion [1] that inspired this work, we have not found any studies on the use of slime mold algorithms for network planning in energy transmission networks. However, the unique characteristics of slime molds, such as their muscleless movement, chemosensory perception, and externalized spatial memory system, have attracted attention as potential research models for optimization problems.

One notable approach proposed by Himmelstein in [1] suggests using slime molds, particularly Physarum polycephalum (PP), for network planning in energy transmission networks. This approach offers advantages over traditional human planning methods, especially in scenarios such as post-electromagnetic pulse (EMP) attack restoration, where quick power grid restoration is crucial.

To expedite the network reconstruction planning process, the SISMO (SImulation of Slime MOlds) algorithm used. SISMO is inspired by the behavior of PP. The SISMO algorithm effectively forms networks, identifies shortest paths, and overcomes obstacles [2], [3]. It has shown promise in network optimization tasks, including transportation network planning.

Research has also demonstrated that PP networks exhibit efficiency, fault tolerance, and cost characteristics comparable to real infrastructure networks [4]. PP creates tubular networks that directly connect food sources, demonstrating adaptive behavior and optimization of nutrient and signal exchange [5], [6].

In the broader field of self-organization and organic computing, the concept of incorporating biological principles into computer systems has gained attention. Self-organization aims to create robust and adaptable systems that can autonomously adapt to changing environments while operating within defined rules and constraints [7]. Organic computing is an approach to designing complex computer systems inspired by the principles of biological systems, such as self-organization, self-adaptation, and self-repair. The goal of organic computing is to create robust and trustworthy systems that can autonomously adapt to changing environments while operating within defined rules and constraints [8]. Organic computing techniques, inspired by biological systems, have been explored in various fields, including multi-energy networks [9].

In [10], Weikert et al. apply organic computing solutions to provide self-organised task allocation solutions in IoT Networks.

Amjad et al. explore the use of bio-inspired techniques, including Enhanced Differential Evolution, Bacterial Foraging Algorithm, and Grey Wolf Optimization, in smart grid scheduling for improving electricity consumption and system reliability. [11]

K.R. Vadivelu and G.V. Marutheswar focus on utilizing the "Fast Voltage Stability Index" (FVSI) for determining maximum loadability and identifying critical transmission lines [12]. Ngo Minh Khoa et al. investigate impedance-based fault location methods in electrical transmission lines and find that the reactance method is the simplest but accuracy depends on fault resistance and location [13]. Data availability is crucial for selecting the right method to improve power system reliability.

III. SISMO (Simulation of Slime Molds)

The SISMO algorithm was implemented in NetLogo [14], a freely available programming language designed for multi-agent systems. Previous studies have shown that NetLogo can conduct simulations involving several thousand agents within a reasonable computational time frame [15], [16]. Flowchart 1 depicts how the algorithm operates within the NetLogo framework, outlining the steps involved in the slime mold network's search for food sources, spread towards them, and formation of the shortest possible path. The SISMO algorithm is based on the first three phases of the slime mold algorithm (SMA) [17] foraging process, which are the search for food, approach to food, and wrapping of food. In the food search phase, pseudopods explore potential food sources in all possible directions randomly. The search range bounds that define the area in which the slime mold can move are set using parameters LB and UB in SMA. In contrast, SISMO defines these boundaries based on the world model settings in NetLogo. Once a pseudopod locates a food source, it moves towards it during the foraging phase, following NetLogo's propagation pattern known as the wiggle function, which differs from the arbitrary alternating positions of pseudopodia in SMA. The pseudopod considers the food source as a point during the food approach phase [2], [3]. The simulation ends when all food sources have been explored by the simulated slime mold. This condition relies on global knowledge that would not be available to a natural slime mold and is not part of the core algorithm. Figure 1 shows a flowchart of the SISMO algorithm.

A. Instructions

SISMO is available on GitHub as open-source software under a Creative Commons license [18]. To run simulations using SISMO, an installed version of NetLogo is required. Upon clicking on the SETUP button, the plasmodium, the chosen number of food sources, and the initial pseudopodia will be created. The simulation can be initiated using the GO button. The number of initial pseudopodia can be set using the AMOUNT-PSEUDOPODIA slider, while the AMOUNT-FOODSOURCES slider sets the number of food sources. The SHOW-NUTRIENT-VALUE switch determines whether or not the nutrient value of the food sources is displayed. The SHOW-NETWORK switch decides whether or not to display the created network required for the A* algorithm. The SHOW-INTERSECTION-POINTS switch controls the display of the calculated intersection points.

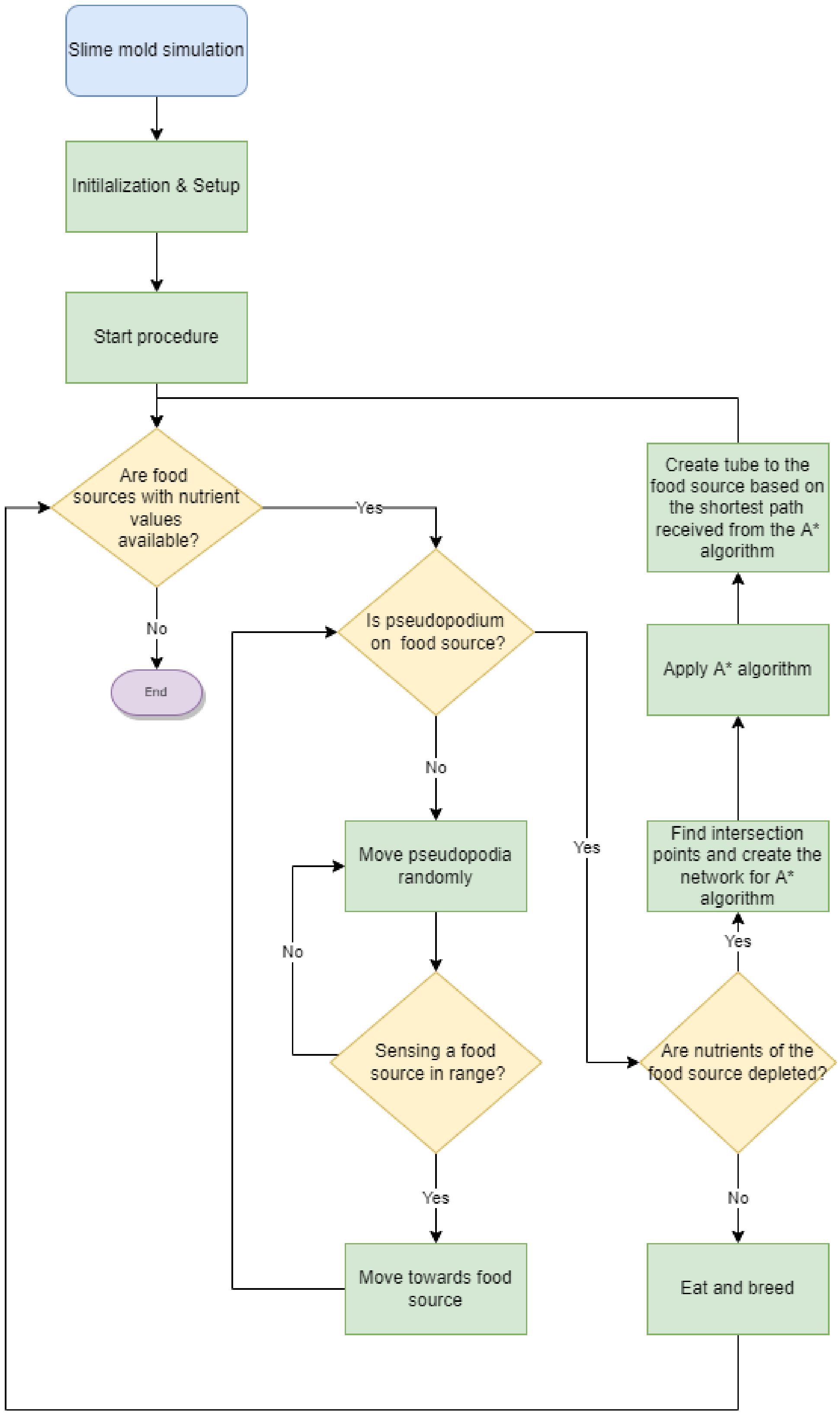

Fig. 1. NetLogo SISMO Algorithm

B. Initialization and Setup

During initialization, the NetLogo GUI allows users to configure simulation parameters. These parameters include the number of pseudopodia, food sources, and options to display nutrient values, the network, and intersection points. The initialization process involves creating agent types (breeds) with their properties and values. The simulation uses six distinct breeds: Plasmodium (the core of the slime mold and starting point for calculating the shortest path), Pseudopodia (responsible for foraging), Tubes (visualizing the shortest path), Foods (food sources), Networkpoints (used in the A* algorithm), and Searchers (used to calculate the shortest path). In the setup phase, all pre-defined breeds, along with their corresponding attributes, are generated. This process includes creating each breed, defining their properties, assigning values to their traits, and ultimately displaying the plasmodium, pseudopodia, and food sources.

C. Simulation Process

The SISMO algorithm mainly involves the simulation process that consists of four primary components: movement, feeding and breeding, network construction, and pathfinding. Initially, all pseudopodia agents are generated with their respective attributes and are allowed to move randomly left or right and forward one step. They cannot move beyond the map limits and instead bounce off the edge. During this movement, the agents pick up nutrients from any food sources they encounter. A new pseudopodium is generated if a random number generated after movement is less than or equal to 0.05. The hatching probability was chosen empirically based on several experiments, where 5% gave the best results. This new pseudopodium inherits all its parent's properties except the ID and has a new path list. The construction of the network involves considering all paths traveled by the pseudopodia, and the intersection points are found and entered into the path list or created as new nodes. Figure 2 displays the visual output of the SISMO simulation in NetLogo after a run. The image illustrates the shortest routes between the core and food sources with a thick yellow path, while the network points are represented by blue dots, and the intersection points are marked in red.

D. Network Building and Pathfinding

To simulate the slime mold's behavior in finding shortest paths within its network [19] the SISMO algorithm utilizes the A* algorithm. The network construction involves storing all pseudopodia paths in a list of path lists, avoiding overlaps by comparing and identifying intersection points. The modified implementation of Caparrini's General A* Solver in NetLogo [20] calculates the shortest path. The optimal path is visually represented as a thicker yellow line, reflecting the efficiency of the A* algorithm and inspired by slime molds' natural behavior.

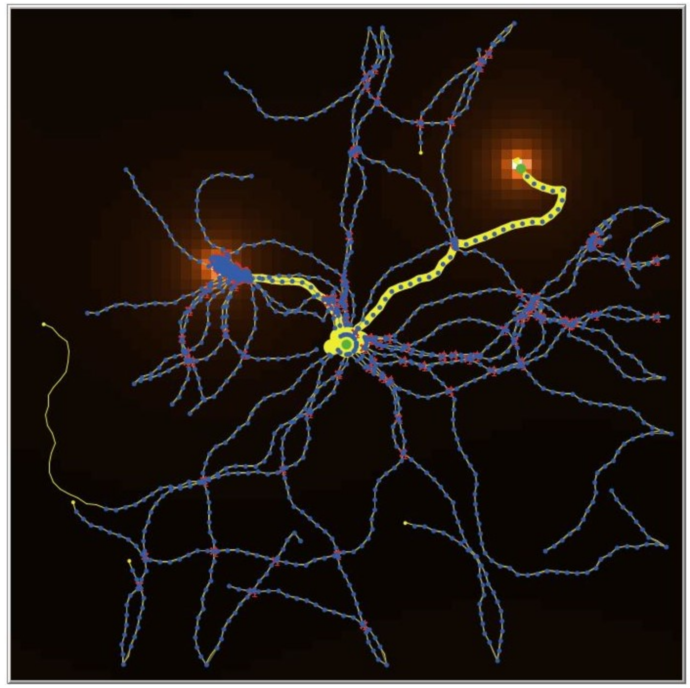

Fig. 2. SISMO Algorithm: Simulation with Shortest Path (yellow), Network Nodes (blue), and Intersection Points (red)

E. Adaptions for Applying to Power Transmission

Originally designed and tested for transportation networks, SISMO exhibited promising performance. However, with some modifications, SISMO can also be applied to various other types of networks. In this paper, we present an adaptation of SISMO for power transmission networks, which required some modifications.

To initiate the NetLogo simulation of the slime mold, a suitable background is required. In this case, the outline of Carinthia's map is imported as the background since the simulation aims to plan the transmission network of the region. To create the world of the model, stationary agents known as patches are utilized in NetLogo, and their size is set to 30. Additionally, the size of the map is adjusted to fit the simulation requirements, with a chosen size of 25 x 10 patches. The frame rate is configured to 10 FPS. In order to model the substations and power plants of the transmission network, feed sources were positioned on the map according to their corresponding coordinates. The data for these locations was obtained from an overview of the Carinthian network infrastructure [21], with a total of 63 participants being observed in the simulation. The coordinates for the locations were converted into a format compatible with NetLogo. This involved creating a program that utilized the same background and size as the NetLogo simulation. By selecting the desired locations, the program outputs the corresponding coordinates that could be used in NetLogo. For each simulation run, specific adjustments were made to the settings. These adjustments were tailored to the individual simulation and involved modifying the number of pseudopodia initialized at the start, adjusting the hatching probability of the pseudopodia, and altering the nutritional values of the food sources. The nutrient value n decreases by 1 at each tick. There is a probability of pseudopod division, the hatch-probability p.

The number of cell divisions follows a binomial distribution. The hatch probability of pseudopodia in the simulation is based on the behavior of slime molds to divide their nuclei every few hours. As a result, an expected value of $n \cdot p$ new pseudopodia arise per food source. If the simulation starts with a single pseudopod, then for 63 food sources each with a nutrient-value of $n = 10$, in the end of the simulation a total of approximately $63 \cdot 10 \cdot 0.05 \approx 31$ pseudopodia are expected. The SISMO version adapted for energy networks is open source and freely available [22].

IV. Rearranged Graph Models

In networks that have been created in a natural environment following geomorphic and infrastructure constraints, we frequently encounter situations where the geographical positions of nodes in a network do not align with the actual connections between them. This can result in short distances between nodes with no existing edges, which may tempt the slime mold algorithm to create connections where there should be none. To address this issue, previous research [1]–[3] has suggested the concept of forbidden areas that the algorithm cannot traverse. However, we propose a different approach in which the layout is adjusted based on the existing network connections. To achieve this, we rely on layout algorithms provided within the Gephi software [23].

Graph layout algorithms rearrange the positions of nodes within a network without modifying the network's nodes and edges. In Gephi, these algorithms aim to enhance the visualization and comprehension of a graph. Additionally, some of these algorithms can align node positions with their connectivity, placing connected nodes closer to each other while pushing unconnected nodes further apart. By applying a graph layout algorithm as a preprocessing step to rearrange the positions of network nodes based on the network structure, our goal is to enhance the accuracy and usefulness of the SISMO results.

We explore a selection of network layout algorithms that primarily simulate physical forces among nodes and edges to determine their optimal positions. Additionally, one algorithm in our consideration focuses on a circular layout.

- Force Atlas: A force-directed layout algorithm that simulates physical forces to position nodes in a graph. [23]
- Force Atlas2: A variation of Force Atlas that includes a multi-level approach to improve the layout quality and scalability of larger graphs. [24]
- Fruchterman-Reingold: A force-directed layout algorithm that balances attractive and repulsive forces to spread nodes evenly in a graph. [25]
- Yifan-Hu Propotional: A force-directed graph layout algorithm that minimizes edge crossings and adjusts node sizes proportional to their degrees. [26]

The graph of the Carinthian transmission network, with the node positions derived from geographical coordinates, was imported into the Gephi tool for creating optimized layouts. Based on the original network, new node layouts were created using the parameters outlined in Table I. As shown in Figure 3, the resulting node layouts produced by Force Atlas and Force Atlas2 were very similar, also with the Yifan-Hu Proportional layout exhibiting some similar characteristics. In contrast, the Fruchterman-Reingold layout was distinct due to its circular shape.

The layout algorithms commonly used for untangling networks on a 2D plane are well-suited to the requirements of the SISMO simulation. In most cases, using linear coordinate scaling, it was straightforward to map a layout optimized for a rectangular viewing window to an input set of nodes for SISMOs simulation space. However, the Fruchterman-Reingold layout, which follows a circular layout with the goal of providing a visually pleasing network depiction, was found to be less useful for the SISMO simulation. This is because nodes in this layout tend to have the same distance to their neighbors regardless of whether an edge exists between them. Therefore, Force Atlas, Force Atlas2, and Yifan-Hu Proportional have been chosen as candidates for further SISMO simulations.

V. Results

The simulations described in this paper were conducted on a computer equipped with an AMD Ryzen Threadripper 3960X processor, running the Windows 11 operating system and the Windows version of Netlogo 6.2.2. The processor has a base clock rate of 3.79 GHz and features 24 cores. In the context of our application, the use of Netlogo involves the use of a single core for each simulation. Consequently, single-thread performance is more relevant to our application case than the number of cores.

TABLE I
Parameters used for layout algorithms

Force Atlas		**Force Atlas 2**	
Inertia	0.1	Tolerance	1.0
Repulsion strength	200.0	Approximation	1.2
Attraction strength	10.0	Scaling	10.0
Max. displacement	10.0	Gravity	1.0
Auto stabilize	enabled	Edge weight influence	1.0
Autostab strength	80.0		
Autostab sensibility	0.2		
Gravity	30.0		
Speed	1.0		

Fruchterman-Reingold		**Yifan Hu Proportional**	
Area	20.0	Optimal Distance	20.0
Gravity	10.0	Relative Strength	0.2
Speed	1.0	Initial Step Size	20.0
		Step ratio	0.95
		Adaptive cooling	enabled
		Convergence threshold	1.0E-4
		Quadtree max level	10
		Theta	1.2

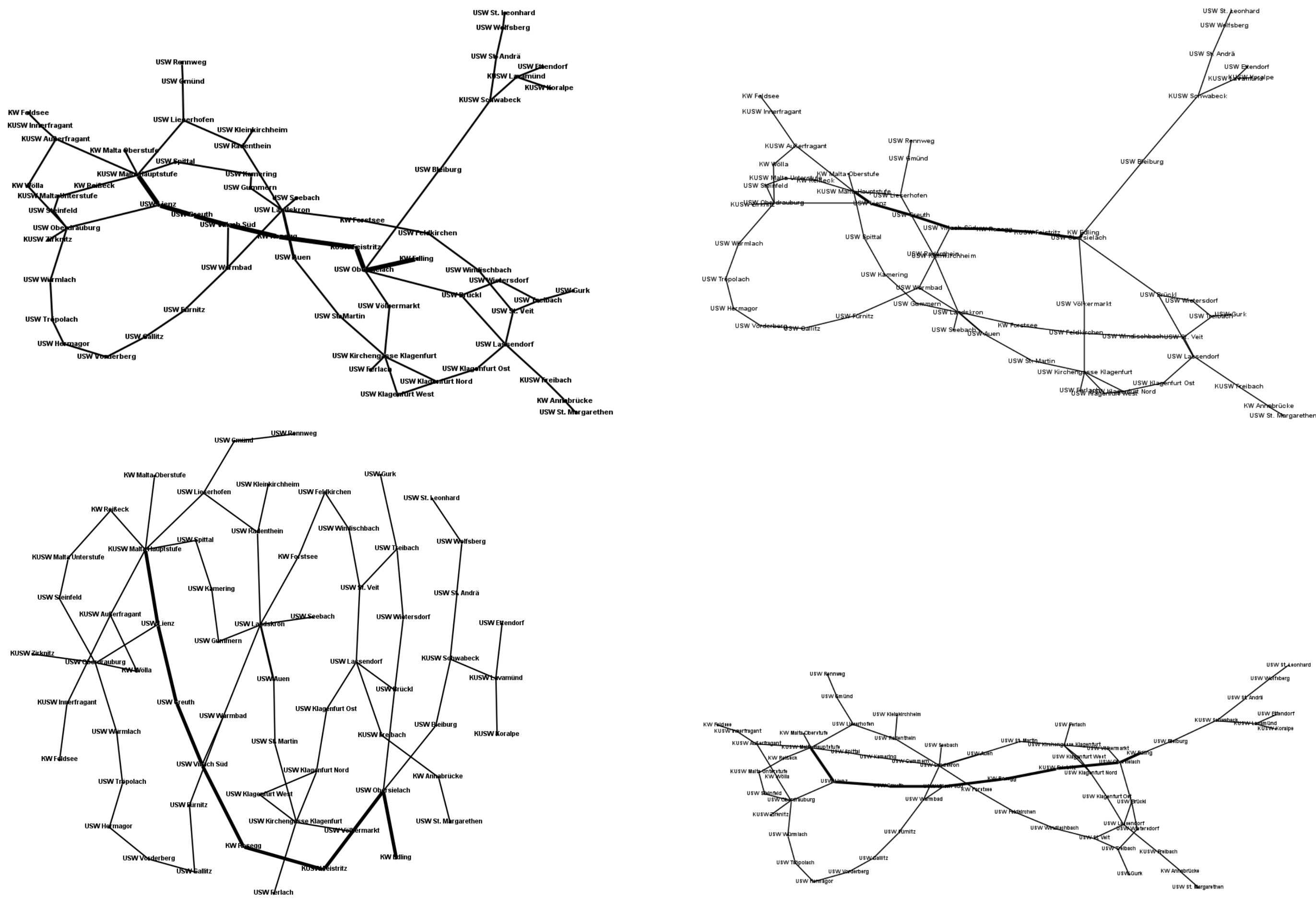

Fig. 3. Rearranged graph following the Force Atlas (upper left), Force Atlas 2 (upper right), Fruchterman-Reingold (lower left) and Yifan-Hu (lower right) algorithms

A. Simulation of the Original Model

To simulate the actual power transmission network in Carinthia, the settings described in section *Adaptions for Applying to Power Transmission* were used. In order to ensure consistency across all simulations, a deliberate choice was made to create the plasmodium and a pseudopod at the center of the map as the starting point.

Eight simulations were conducted in total using the original network, with an average simulation duration of 50 minutes and 5 seconds. Figure 4 illustrates the outcomes of one of the simulations conducted on the Carinthia power transmission network in its original state. The plasmodium is represented by the yellow cloud located at the center of the map. The simulation model includes the generation of a pseudopodium that initially moves away from this plasmodium. The map contains several food sources, which are represented by black dots with orange frames. These food sources are placed at the coordinates of substations and power plants (black circles). The simulation generates orange lines to represent the paths traveled by the pseudopodia. From the resulting network, the simulation model identifies the shortest paths traveled between the food sources. These shortest paths are then graphically represented on the map with thicker yellow lines.

Taking into account the performance metrics, the simulation of the original network using SISMO achieved 29 true positives, 1821 true negatives, 60 false positives, and 43 false negatives. True Positives (TP) represent the connections that were correctly identified as actual connections where they should exist, while True Negatives (TN) represent the absence of connections where there shouldn't be any, and the simulation correctly identified these cases. False Positives (FP) are cases where the simulation introduced connections that do not exist in the real network. False Negatives (FN) signify cases where the simulation did not create a connection although there exists such a connection in reality. The precision is calculated as 0.33. This means that out of all the connections identified by the simulation, 33% were actually true connections, while the remaining 67% were false positives. The recall is calculated as 0.4, indicating that the simulation successfully detected 40% of the total connections present in the power transmission grid. With an F1-score of 0.36, we can conclude that the simulation achieved a moderate balance between precision and recall, but there is room for improvement. These metrics demonstrate

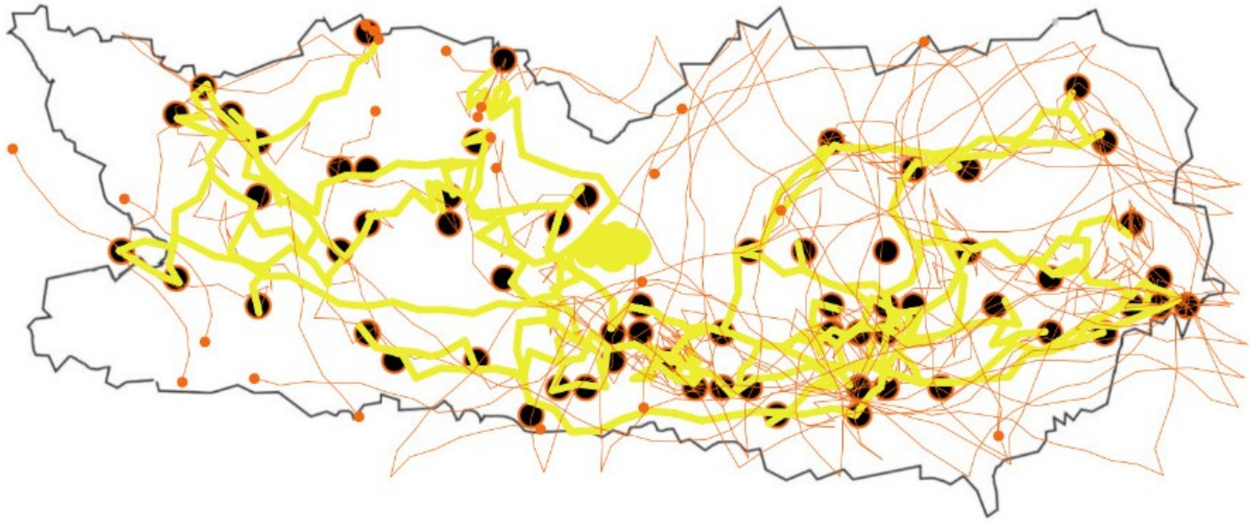

Fig. 4. Simulation of the Original Model

the simulation's capability to identify connections within the power transmission grid, but it also highlights the challenges faced in accurately detecting all connections.

Simulations based on the Graph Visualization Models

B. Simulation of Force Atlas Layout

The Force Atlas layout algorithm was simulated using the same settings as before. The average simulation duration was 07 hours 18 minutes and 46 seconds.

The outcome of one of the simulations conducted for the first optimized layout using Force Atlas 1 is displayed in Figure 5. The plasmodium, depicted as a yellow cloud, is situated at the center of the graph. The orange lines demonstrate the paths followed by the pseudopodia. The locations of the food sources correspond to the coordinates of the substations and power plants in the optimized graph (white dots). The orange lines represent all paths traveled by the pseudopodia. The shortest distance traveled between these points is illustrated as a thicker yellow line.

The Force Atlas 1 simulation achieved 34 TP and 1821 TN. There were 60 FP and 38 FN. The precision is 0.36, while the recall is 0.47. The F1-score of the Force Atlas 1 simulation is 0.41.

C. Simulation of Force Atlas 2 Layout

Ten simulations of the optimized network with Force Atlas 2 were performed with the same settings and initial values as the previous simulations. The simulations had an average duration of 1 hour, 42 minutes, and 4 seconds.

Figure 6 shows the result of one of the simulations with SISMO on the Force Atlas 2 diagram. Food sources were placed based on the diagram's coordinates (white dots). The orange and yellow lines represent the paths taken by the plasmodia, with the thicker yellow lines indicating the shortest paths. In the Force Atlas 2 simulations, there were 33 TP connections and 1815 TN. However, 66 FP and 39 FN were identified. The simulations achieved a precision of 0.33. The recall was calculated as 0.46. The F1-score was determined to be 0.39.

D. Simulation of Yifan-Hu Proportional Layout

The Yifan-Hu Proportional Algorithm was employed to optimize the map in the simulation, while keeping all other simulation settings consistent with the previous experiments. The ten conducted simulations utilizing the Yifan-Hu Proportional graph algorithm had an average duration of 5 hours, 14 minutes, and 13 seconds.

The result of one of the simulations of the Yifan-Hu Proportional graph is presented in Figure 7. Based on the coordinates of the optimized graph, feed sources were placed on the map. The paths traveled and the shortest connections created are also visible in this figure. The simulation of the Yifan-Hu Proportional graph achieved 37 TP, 1818 TN, 63 FP, and 35 FN. The precision is calculated as 0.37. The recall of 0.51 signifies that the simulation successfully detected 51% of the total connections present in the power transmission grid. The F1-score for recreating the original network is 0.43. A higher value is generally better, although we don't aim at a full recreation of the original network. Therefore, some FN can be interpreted as a means to thin out the network, which might reduce repair effort. On the other hand, FN represent connections which were not present in the first place. Here the original network layout yields a significantly worse value than the rearranged graph models.

VI. EVALUATION

Our adaptation of the SISMO simulation aims to create a dynamic and interconnected power transmission network that can respond to substation or power plant outages, increasing grid reliability. This is achieved by creating a connectable and

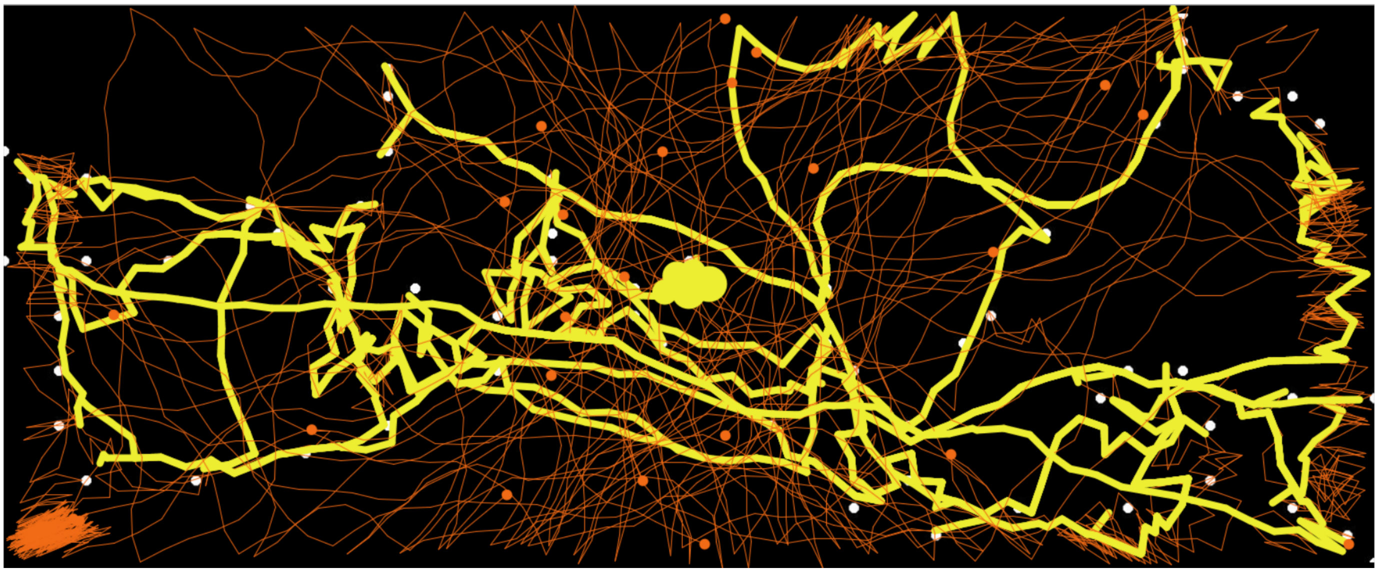

Fig. 5. Simulation of the Force Atlas Model

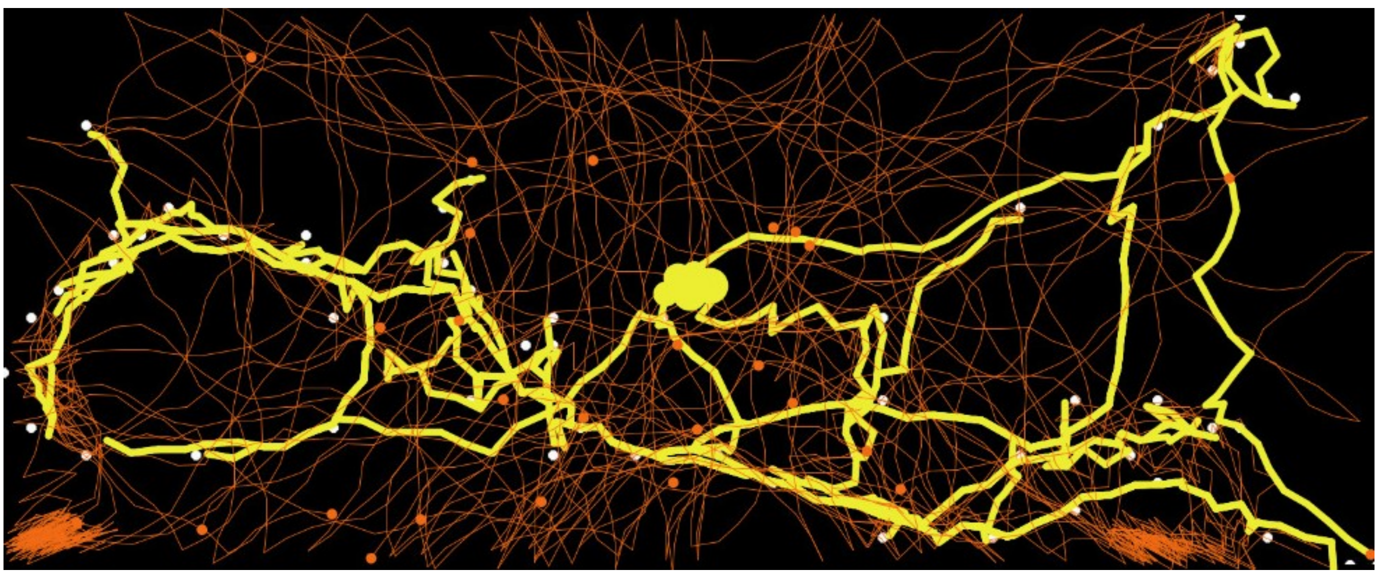

Fig. 6. Simulation of the Force Atlas 2 Model

dynamic system that allows for the continuous flow of energy from various sources into the grid. The network's redundancy enables it to rely on multiple power sources, allowing it to switch to another source in case of failures. This resilience would be particularly beneficial in restoring power after an electromagnetic pulse (EMP) attack.

However, the resulting network generated by SISMO contains connections between network points that do not have an existing power line, as SISMO is unaware of feasible and infeasible network paths. This was especially problematic with the geographical node distribution, which yielded only a F1-score of 0.36 with a average simulation time of 50 minutes and 5 seconds. To address this issue, graph visualization algorithms were applied as a preprocessing step, resulting in an improvement in the number of reconstructed paths and a better overall F1-score. All values for TP, TN, FP, FN, as well as precision, recall, and F1-score are presented in Table II. The F1-score comparison among the simulations shows that all simulations using the rearranged graph models outperformed the simulation conducted on the original network. The rearranged graph models achieved higher F1-scores, demonstrating a better balance between precision and recall. With 0.43 the simulations of the Xifan-Hu model achieved the highest F1-score.

VII. Conclusion

In this paper, we implemented Himmelstein's approach to repairing energy networks using a slime mold-inspired

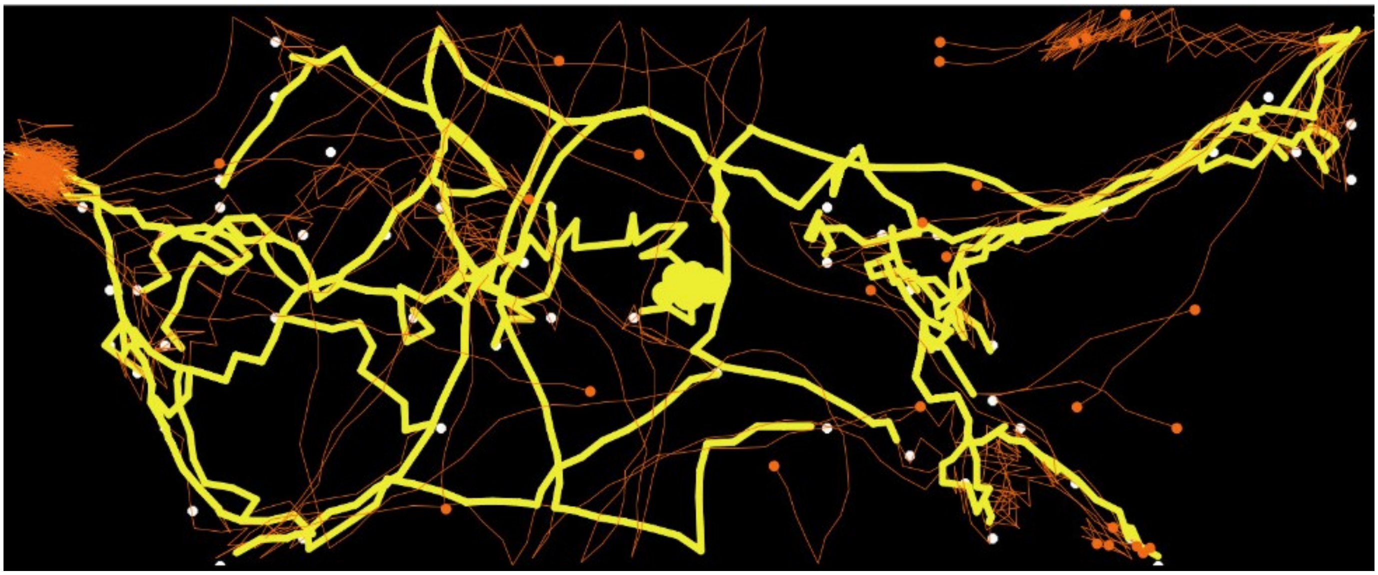

Fig. 7. Simulation of the Yifan-Hu Propotional

TABLE II
COMPARISON OF THE SIMULATION RESULTS

	Avg. Duration	TP	TN	FP	FN	Precision	Recall	**F1-Score**
Original network	00:50:05	29	1821	60	43	0.33	0.4	**0.36**
Yifan-Hu	05:14:13	37	1818	63	35	0.37	0.51	**0.43**
Force Atlas 1	07:18:46	34	1821	60	38	0.36	0.47	**0.41**
Force Atlas 2	01:42:04	33	1815	66	39	0.33	0.46	**0.39**

method. However, we used the SISMO simulation system instead of the original proposal, which mimics the behavior of a real Physarum polycephalum slime mold. Unfortunately, the outcomes fell short of the desired outcome. Repeated simulations demonstrated that employing the slime mold approach often yielded networks that were fragmented or contained non-existent connections, rendering it less applicable for effectively prioritizing repairs in an established energy network. The problem of introducing non-existent network connections was addressed using the approach presented in this paper, which employs graph visualization algorithms, particularly the Force Atlas, Force Atlas2, and Yifan-Hu Proportional algorithms. These algorithms improved the results by reorganizing the layout based on the existing network connections, but also increased computation time due to the nodes being more spread after processing with a layout algorithm.

As discussed in the introduction, using slime molds as the architect for network design potentially offers several advantages over traditional human planning approaches, particularly in the context of large complex networks. However, in the specific use case of repairing a power transmission system, the number of decisions for the next repair step is comparatively low. In such scenarios, alternative approaches like minimum spanning trees and shortest network routes between relevant nodes could provide more straightforward solutions. Furthermore, while slime mold simulations can yield valuable insights, it is crucial to note that in the use case of this paper, the output requires further processing to address impossible connections. Although graph layout algorithms have shown improvements in mitigating this problem, it has not been entirely eliminated. Thus, the practical application of the slime mold approach remains a subject for future research and development.

To the best of our knowledge, the work presented in this paper is the first to propose the use of graph visualization algorithms for bio-inspired algorithms such as the slime mold simulation. This approach has promising potential for a wide range of applications where algorithms are not constrained by physical or infrastructure limitations that may have influenced the original network connections. Further exploration of this approach could yield significant insights into various fields.

To facilitate future work, we plan to include an importer tool in the SISMO software that incorporates the ability to run either Force Atlas, Force Atlas2, or Yifan-Hu Proportional algorithms and does the necessary scaling for SISMO. This importer would support processing any node layout based on a network structure.

APPENDIX

The substations and power plants of the Carinthian power transmission grid are presented in an alphabetically ordered list in Table III. Each substation and power plant is assigned a unique number, which is used for identification throughout the paper.

AVAILABILITY OF DATA AND MATERIALS

All data and code will be made available in a Git repository before the conference date. SISMO[1] and Gephi[2] are available as open source.

[1]https://github.com/smartgrids-aau/SISMO
[2]https://gephi.org/

TABLE III
LIST OF LOCATIONS

No.	Locations	No.	Locations
1	KUSW Außerfragant	33	USW Kirchengasse Klagenfurt
2	KUSW Feistritz	34	USW Klagenfurt Nord
3	KUSW Freibach	35	USW Klagenfurt Ost
4	KUSW Innerfragant	36	USW Klagenfurt West
5	KUSW Koralpe	37	USW Kleinkirchheim
6	KUSW Lavamünd	38	USW Landskron
7	KUSW Malta Hauptstufe	39	USW Lassendorf
8	KUSW Malta Unterstufe	40	USW Lienz
9	KUSW Schwabeck	41	USW Lieserhofen
10	KUSW Zirknitz	42	USW Oberdrauburg
11	KW Annabrücke	43	USW Obersielach
12	KW Edling	44	USW Radenthein
13	KW Feldsee	45	USW Rennweg
14	KW Forstsee	46	USW Seebach
15	KW Malta Oberstufe	47	USW Spittal
16	KW Reißeck	48	USW St. Andrä
17	KW Rosegg	49	USW St. Leonhard
18	KW Wölla	50	USW St. Margarethen
19	USW Auen	51	USW St. Martin
20	USW Bleiburg	52	USW St. Veit
21	USW Brückl	53	USW Steinfeld
22	USW Ettendorf	54	USW Treibach
23	USW Feldkirchen	55	USW Tröpolach
24	USW Ferlach	56	USW Villach Süd
25	USW Fürnitz	57	USW Vorderberg
26	USW Gallitz	58	USW Völkermarkt
27	USW Gmünd	59	USW Warmbad
28	USW Greuth	60	USW Wietersdorf
29	USW Gummern	61	USW Windischbach
30	USW Gurk	62	USW Wolfsberg
31	USW Hermagor	63	USW Würmlach
32	USW Kamering		

AUTHOR'S CONTRIBUTIONS

The first author elaborated the idea together with the third author and conducted the experiments using SISMO. The second author contributed the implementation of the conversion tools to process data with longitude/latitude coordinates in Gephi and to interface Gephi with SISMO. The third author provided the overall idea and conducted the data processing using Gephi. All authors contributed to the writing of this paper.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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