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Leveraging Topological Data Analysis for disaster preparation and response, a cartographic perspective

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Abstract:

Natural disasters, such as hurricanes, can cause road networks to degrade. This degradation can cause a reduction in traffic capacity, making it difficult to efficiently route emergency vehicles and supplies to neighborhoods in need. It is common to model road networks as directed graphs, which provide a formal framework for describing and analyzing traffic flow. Assigning a numeric weight, such as traffic capacity, to each edge allows us to quantify the amount of flow between any two intersections. Formally, this is referred to as a maximum flow problem. For static graphs, there is a family of algorithms that can solve this problem in polynomial time. However, accurate models of infrastructure networks contain a very large number of nodes and edges, so these algorithms become computationally expensive. In dynamic models, where edges are constantly being added and removed, recomputing the maximum flow value from scratch is highly inefficient, motivating the need for a better approach. In areas at risk for natural disasters that may face evacuation needs, understanding the flow patterns through a mapped area under changing conditions is of the utmost importance. This project developed an algorithm to analyze and visualize road network capacity under changing conditions. Representing the networks cartographically allows for a greater understanding of the strengths and weaknesses of a given system before it is placed under stress.

The developed algorithm determines how much the maximum flow value between two fixed intersections changes when an edge is added to the graph. The algorithm starts by computing a maximum flow on the original graph. If the new edge goes from node u to node v, the maximum flow value will increase only if we can push flow from the source to u and from v to the sink. The exact amount the maximum flow value will increase can be determined by solving two smaller maximum flow problems, one from the source to u and the other from v to the sink. These computations are independent and can be performed in parallel to save time. Furthermore, information from previous iterations can be stored and recycled to reduce computational redundancy. Each iteration results in a maximum flow on the graph, ensuring this process can be repeated as more edges are added.

This algorithm can also be used for determining the maximum flow value between two geographic regions. In the context of road networks, this means pushing flow from one collection of intersections to another. Standard maximum flow algorithms only work with one source node and one sink node, but luckily there is an easy fix. Two new nodes called the supersource and supersink can be added to the graph, along with edges connecting them to the desired source and sink nodes, respectively. The capacities of the new edges are set to a very large value so that they do not contribute to any bottlenecks.

The images below were created using the Python package OSMnx along with road network data for Corvallis, Oregon and show an example of pushing flow from one region to another. The green nodes are the sources, and the red nodes are the sinks. A wildfire in 2014 was the inspiration for this example, as the green nodes roughly reflect the areas that were forced to evacuate. The red nodes are parking lot entrances for a nearby school and church, which could have been used as supply centers for the people evacuating. The cyan paths show the routes along which flow is being pushed, and their widths indicate the quantity of flow relative to the other paths. In Figure 1, the road network is intact. In Figure 2, a collection of edges near the bottom right was removed. To apply the above algorithm, the bottom image was the base graph, and the missing edges were added one at a time. The result was that the maximum flow value increased, which can be seen by the addition of a third flow path between the green evacuating nodes and the red resource nodes.

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Figure 1. Sample pushed flow of network data from Corvallis, OR. Green nodes represent areas evacuated in a 2014 wildfire, red nodes are public gathering spots.

Future work will include trying to improve the algorithm for dynamic infrastructure models and making the process for creating images easier as well as further integration into cartographic products such as regional maps for disaster response and planning. The long-term goal of this project is to provide a comprehensive tool for understanding the stability of road networks in geographic regions susceptible to degradation. This information could be used to inform the construction of new roads or allow public services to know which neighborhoods of a city are more vulnerable before a disaster occurs.

Figure 2. The same network as Figure 1, but with edges removed from the bottom right to reflect infrastructure impacts of the wildfire.

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