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Moving Toward an Optimal and Automated Geospatial Network for CCUS Infrastructure

Abstract:

Modifications in the global climate are being driven by the anthropogenic release of greenhouse gases (GHG) including carbon dioxide (CO_2) (Middleton et al. 2014). CO_2 emissions have, for example, been directly linked to an increase in total global temperature (Seneviratne et al. 2016). Strategies that limit CO_2 emissions—like CO_2 capture, utilization, and storage (CCUS) technology—can greatly reduce emissions by capturing CO_2 before it is released to the atmosphere. However, to date CCUS technology has not been developed at a large commercial scale despite several promising high profile demonstration projects (Middleton et al. 2015). Current CCUS research has often focused on capturing CO_2 emissions from coal-fired power plants, but recent research at Los Alamos National Laboratory (LANL) suggests focusing CCUS CO_2 capture research upon industrial sources might better encourage CCUS deployment.

To further promote industrial CCUS deployment, this project builds off current LANL research by continuing the development of a software tool called SimCCS, which estimates a regional system of transport to inject CO_2 into sedimentary basins. The goal of SimCCS, which was first developed by Middleton and Bielicki (2009), is to output an automated and optimal geospatial industrial CCUS pipeline that accounts for industrial source and sink locations by estimating a Delaunay triangle network which also minimizes topographic and social costs (Middleton and Bielicki 2009). Current development of SimCCS is focused on creating a new version that accounts for spatial arrangements that were not available in the previous version. This project specifically addresses the issue of non-unique Delaunay triangles by adding additional triangles to the network, which can affect how the CCUS network is calculated.

CO_2 capture, utilization, and storage

From a broad perspective CO_2 capture, utilization, and storage (CCUS) can be broken down into a simple three step procedure. (1) The capture and compression of CO_2 before it is released to the atmosphere from stationary sources like industrial plants. (2) The transportation of the captured CO_2 through a pipeline network. (3) The injection of the CO_2 into deep geological reservoirs like saline aquifers, deep-sea sediments, or depleted oil and gas fields (Middleton and Bielicki 2009). A fourth and optional step, but one that would improve the economic viability of CCUS infrastructure, involves using the captured CO_2 for other manufacturing processes that produce market-viable products (Middleton et al. 2015).

The ultimate goal of CCUS is to reduce the amount of CO_2 released to atmosphere by storing it deep within the earth's surface for hundreds of thousands of years. At the same time, however, CCUS does not drastically change current energy infrastructures that are already in place. CCUS is, therefore, an important CO_2 mitigation strategy because it can be integrated with the current energy production economy. CCUS offers a short term solution to a long term problem and can be seen as a bridge between the current fossil based energy system and one based on alternative sources (Middleton et al. 2015).

SimCCS

While CCUS has potential to significantly offset CO_2 emissions, for CCUS to be truly effective the infrastructure would need to be deployed at a massive scale. A pipeline network at a massive scale requires extensive planning and cost, so CO_2 emitting industries have, to date, been reluctant to develop a CCUS infrastructure. Therefore a well demonstrated and feasible cost plan should be developed in order to persuade CO_2 emitting industries to mitigate their emissions through a CCUS infrastructure. A crucial step in estimating the cost of CCUS infrastructure is to estimate a realistic, low cost CCUS pipeline network.

Until recently CCUS infrastructure models either ignored or simplified the estimation of the pipeline network. To address this pipeline estimation problem Middleton and Bielicki (2009) developed a software tool called SimCCS, which outputs a realistic, efficient, cost estimating pipeline that connects CO_2 sources and reservoirs. SimCCS accounts for topographic, social, and geometric costs of a CCUS pipeline network in order to accurately portray the economic feasibility of its deployment within a geographic region.

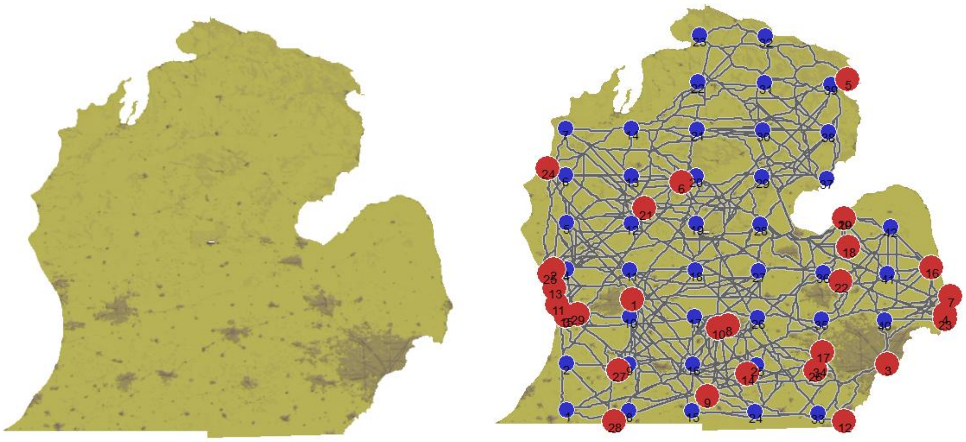


Figure 1: (A) Raw Cost surface of Michigan and (B) locations of sources in red, reservoirs in blue, and the raw pipeline network.

SimCCS Raw Network

In order to estimate the topographic and social costs of a CCUS pipeline network, SimCCS uses a raster cost surface, which is created prior to its use within SimCCS (Figure 1a). Each pixel within the cost surface represents a one square kilometer landscape and has a value that estimates the cost of building a pipeline within that area. SimCCS uses these pixel values to estimate a least cost path (LCP) between each CO_2 source and reservoir within the network (Figure 1b).

SimCCS Candidate Network

The raw network is the preliminary basis for the pipeline network, but it is further refined to account not only for the cost surface, but to also account for an optimal spatial arrangement. This cost and spatial inclusive pipeline network is called the candidate network. To account for an optimal spatial arrangement the candidate networks utilizes Delaunay triangles in order to create an idealized network between sources and reservoirs that is not beholden to real work topography or social cost.

Boris Delaunay was a prominent Russian mathematician who developed a triangulation of planar points that maximizes the minimum angle in any triangle within a network (Musin 1997). By maximizing the minimum angle of any triangle within a network, the Delaunay triangulation ensures that slivered triangles do no occur within the network, thus minimizing the distance between points (Figure 2). Therefore, the Delaunay network is an idealized network that, if not restrained by real work geography, creates a minimized cost network. This characteristic of Delaunay triangulation has made it a useful tool for subjects as unrelated as discrete fracture networks (Hyman et al. 2014; Makedonska et al. 2015) and estimations of animal habitats (Downs and Horner 2009).

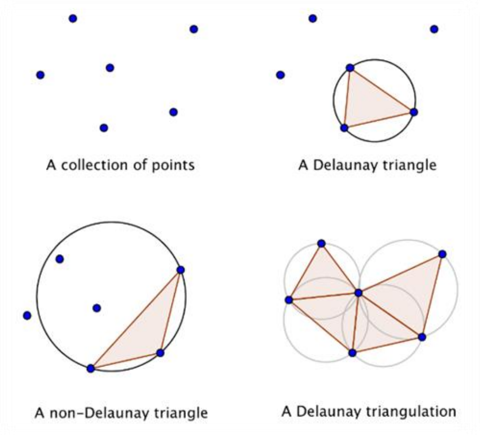
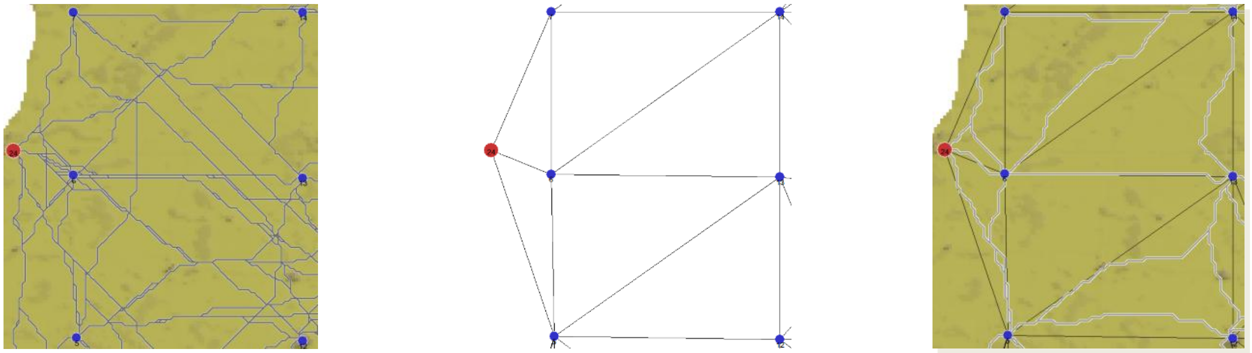


Figure 2: Delaunay Triangles were developed by Boris Delaunay in 1934. They maximize the minimum triangle within any triangle in a network.

While the Delaunay triangulation is ideal, in a real world scenario an estimated pipeline network is restricted by real world costs like topography and social cost. As a consequence, the candidate network uses Delaunay triangulation to create an idealized geometric network and then also accounts for real world cost (Figure 3). The candidate network modeled in SimCCS is an LCP network that also incorporates an optimal geometric shape where no pipeline cost is overly high due to geometric (i.e. distance) cost.



(A) *(B)* *(C)*

Figure 3: (A) Raw network accounting for LCP, but not optimal geometry. (B) Idealized Delaunay Network not accounting for LCP. (C) Candidate Network accounting for LCP and Delaunay Triangulation.

2.2.3 Non-Unique Delaunay Triangulation

While Delaunay triangulation offers a simple solution to network configuration, it does have an inherent problem – the non-unique Delaunay triangulation problem – which occurs when the triangulation can be created in more than one way. For example, non-unique triangulation can occur if four points in a plane are equidistance from one another such that the points, if connected, would make a perfect square or rectangle (Sukumar et al. 2001) (Figure 4).

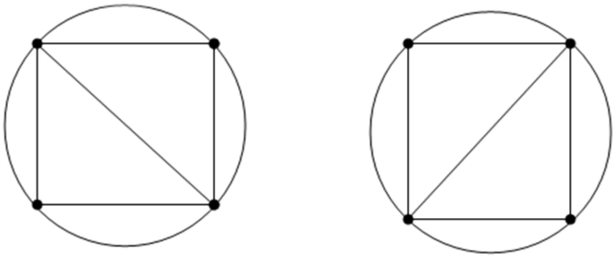


Figure 4: An Example of Non-Unique Delaunay Triangulation.

In a real world CCUS pipeline network, sink and source locations are unlikely to be located in a geographic space where perfect non-unique triangulation would occur. However, there are real world instances where non-unique triangulation can occur within a CCUS pipeline network if the cost surface is also considered. For example, in the state of Michigan source and sink locations almost cause the non-unique Delaunay triangle problem (Figure 5). If the cost surface is also considered within that Michigan pipeline scenario, there are instances where the more cost effective pipeline is an alternative Delaunay Triangulation. For instance, Figure 5 depicts the location of sources and sinks in an area of Michigan. The left configuration within Figure 5 shows the triangulation as outputted by SimCCS; the right configuration depicts a scenario where another Delaunay triangulation is also possible.

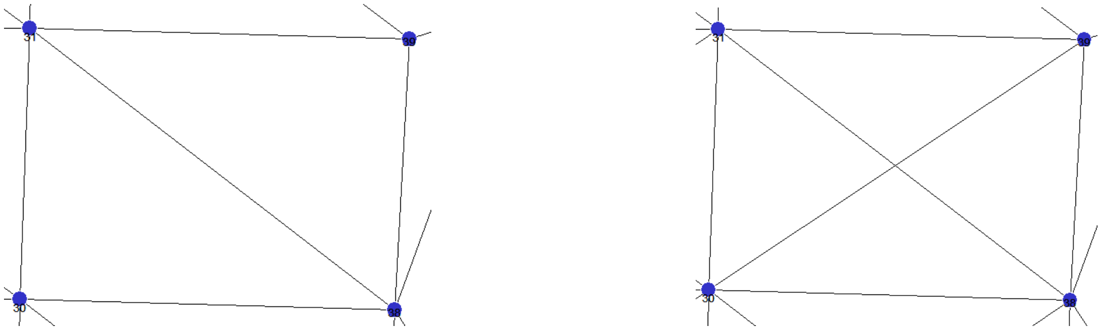


Figure 5: Non-Unique Triangles within a Pipeline Network in Michigan.

In Figure 6 the configuration of the two alternative Delaunay pipelines network is shown with both the Delaunay triangulation scenarios and the cost surface considered. The red line in Figure 6 highlights a pipeline whose cost is less than the pipeline created from the original Delaunay triangulation. This Michigan example demonstrates a real world situation in which the non-unique Delaunay triangulation problem can affect the outcome of a pipeline scenario.

Figure 6: Shown in Red is a less cost prohibitive pipeline than that of its Delaunay counter part, which is intersected by the red line in the image above.

Conclusion

The purpose of this project was to add functionality to SimCCS so that non-Unique Triangulation would be considered within a modelled pipeline network. SimCCS now has an option to add pipelines for non-unique triangulation, which is exemplified in Figure 6. This new functionality moves SimCCS closer to accurately automating and optimizing a cost effective CCUS pipeline infrastructure. More functionality will continue to be added to SimCCS in the future.

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