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A METHODOLOGY FOR OPTIMAL GEOTHERMAL PIPELINE ROUTE SELECTION WITH REGARDS TO VISUAL EFFECTS USING DISTANCE TRANSFORM ALGORITHMS

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ABSTRACT

The objective of this study is to develop a methodology and to create a tool for use in geothermal pipeline route selection. Special emphasis is placed on the method finding the shortest route and minimizing the visual affects of the pipeline. Among other constraints that can be incorporated into the method are: Type of flow regime, pressure drop, building costs, inaccessible areas and maximum allowable gradients. Included in the tool is site selection for separators and pipeline gathering points based on visual effects, land costs, inaccessible areas and total distance to boreholes.

The method uses a combination of variable topography distance transform algorithms and a new extension to multiple weight distance transform algorithms. A method is presented to rank each point in a grid (representing some topography) based on visibility with regards to roads, buildings and public areas. The method works with a digital representation of the geothermal area in question called Digital Elevation Models (DEM) which is a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals. The method is implemented for pipeline route selection in the Hverahlíð geothermal area. The visual effects of the route recommended by the method are compared to those of the shortest possible route and the route proposed in the original planning for the geothermal area.

INTRODUCTION

Route selection in geothermal areas in Iceland is a topic of growing importance. The visual effects of pipelines in Icelandic geothermal areas are a debated topic in Iceland and demands for burying pipelines to eliminate the visual effects are growing louder, both from the public at large and the government. This would however significantly increase the costs of geothermal power plants, rendering less the feasibility of utilization of new geothermal areas. It is therefore desired to minimize the visual effects of the pipelines.

In the geothermal industry today, ad hoc methods are mostly employed for pipeline route selection. GIS based systems are employed for manual selection of pipeline routes. It is endeavored to keep the pipeline route as short as possible and to minimize turns and incline. The most important aspect is usually to keep the route monotonic and the incline slight in order to minimize pressure drop and slug flow conditions in the pipeline. Routing techniques have been developed using many optimization techniques. Metaheuristic algorithms have been used extensively. Genetic algorithms, simulated annealing and ant colony optimization, particle swarm optimization, differential evolution, harmony search, glowworm swarm optimization, intelligent water drops, evolution strategies have all been used for vehicle routing techniques.

Distance transforms (DT) are image processing methods for digital images. They were first introduced in the paper “distance functions on digital pictures” (Rosenfeld & Pfaltz, 1968). A DT finds the distance from each object point to pixel in an image and maps the value of the distance to the closest object point. In this paper chamfer distance transforms are utilized, using the optimal chamfer values presented by Borgefors (Borgefors, 1986). Calculating distances over 3-D surfaces can be very computationally intensive. The Variable Topography Distance Transform (VTDT) introduced by Smith (Smith, Determination af gradient and curvature constrained optimal paths, 2005) offers a simpler way to deal with this problem. 3-D land surfaces are essentially open 2-D manifolds, which renders the use of a distance transform possible. Gradient and curvature constraints along with inaccessible areas are implemented in the algorithm through the use of digital elevation models (DEM).

The use of VTDT has been proposed for geothermal pipelines in order to find the shortest route (Kristinsson, 2005), showing good results. The method employed in this paper extends his method while also modifying the algorithm used and introducing a new method of visual effects ranking, the method of Kristinsson is then modified to better suit finding the optimal path with regards to visual effects. A digital elevation model (DEM) or a digital terrain model (DTM) is a digital representation of a ground topography. DEM's are most commonly constructed using remote sensing techniques and also by land surveying. DEM's are available for the majority of Icelandic topography. A DEM is a 2-D matrix where each element represents the height at the corresponding surface location. DEM's are utilized in this paper to incorporate gradient constraints. Smith (Smith, Distance transform as a new tool in spatial analysis, urban planning and GIS, 2004) also introduced the Multiple Weight Distance Transforms (MWDT). A MWDT is an algorithm that utilizes multiple distance transforms, weighted based on relative importance, to find a minimum with regard to multiple criteria. Resulting from a MWDT is a composite surface with one or more minima. This can be used to solve the Steiner problem and is utilized in this paper with additional constraints to obtain the optimal location for separators and power plants.

To find the shortest path with distance transform algorithms two different approaches are possible. First of all, the shortest path is known to be orthogonal to the distance isolines (distance bands), therefore the algorithm can perform a distance transform for the starting point of the pipeline and then the pipeline route is orthogonal to each isoline until it reaches the end point. A more effective method is to record the incremental path movements as a part of the distance transform algorithm. That is, the algorithm can be amended to record for each point in the grid, what direction the next pixel in the shortest path is. While this is essentially the same method as the previous one, this representation gives smoother and better results and requires less computation time.

This paper extends Kristinson's and De Smith's method to include multiple costs. Furthermore the use of DT's to rank surface locations based on visual effects is introduced and the Multi-objective Least Cost Distance Transform (MLCDT) is introduced to obtain the optimal route with regards to visual effects, length, pressure drop, flow regime and land accessibility.

The major innovation in this paper is the utilization of DT's to rank areas (image pixels) based on visibility from roads, buildings and other sites where it is desired to minimize the visibility of pipelines. This paper presents a complete tool for the selection of pipeline route in geothermal areas which includes the selection of power plant and separator sites.

VTDT AND MWDT ALGORITHMS

The central function for a standard distance transform algorithm is:

$$d_0 = min(d_k + LDM(k), d_0)$$

1)

The algorithm places a mask in parallel on each pixel in an image. Here "d_0" represents the current value of the pixel, "d_k" is the value of the k-th element of the mask and "LDM(k)" is the local distance metric, or the distance from the pixel being processed to the k-th element in the mask. For each pixel, if the value of the k-th element in addition to the local distance metric is smaller than the previous pixel value, the value is changed. The results of employing a DT algorithm on a digital image are a matrix where all the elements have the value of the distance to the closest image pixel.

A VTDT algorithm, as previously mentioned extends the use of DT's to 3-dimensional surfaces through the use of DEM's. The slopes between pixels in the mask are calculated and incline constraints implemented as shown below. The central function for the VTDT algorithm is:

$$slope = \frac{DEM_k - DEM_0}{LDM(k)}$$

2)

$$if(\ d_k + LDM(k) < d_0\ \ \&\&\ \ slope < MaxSlope);$$
$$then:\ d_0 = d_k + LDM(k)$$

3)

where DEM_k represents the value of the digital elevation model for the k-th element of the mask.

If $[DT(A]_i)$ is defined as the distance transform on the set A_i and k_i is the relative weight of each distance transform, the MWDT is defined as:

$$z = \sum_{i=1}^{n} k_i DT(A_i)$$

4)

Incline and other constraints are implemented in each respective distance transform as shown above. The composite surface resulting from a MWDT algorithm indicates the solution to the constrained Steiner problem.

MULTI-OBJECTIVE LEAST COST DISTANCE TRANSFORM ALGORITHM (MLCDT)

The distance transform algorithm can be modified to incorporate cost functions of variables to be optimized, for an example land costs and visual effects. This was first presented by Smith (Smith, Distance transform as a new tool in spatial analysis, urban planning and GIS, 2004) as the Least Cost Distance Transform algorithm (LCDT) and is extended here to incorporate multiple cost variables (as suggested by Smith). The costs of each variable need to be defined in each pixel and these costs are then multiplied to the incremental distance to each lattice point. The central function of a MLCDT with n cost variables is:

$$d_0 = min(d_k + LDM(k) * (C_1(x,y)+..+C_n(x,y)), d_0)$$

5)

where “$C_n(x,y)$” is the cost of the n-th cost element in lattice point (x,y). The extension to the VTDT is:

$$slope = \frac{DEM_k - DEM_0}{LDM(k)}$$

6)

$$if(\ d_k + LDM(k) * (C_1(x,y)+..+C_n(x,y)) < d_0\ \&\&\ \ slope <$$
$$then:\ d_0 = d_k + LDM(k)$$

7)

which is the exact same algorithm as in the VTDT, except that each element in the mask is multiplied by its respective costs.

The isolines generated by this algorithm are equal cost isolines and the surface created is an accumulated cost surface. It is necessary when employing a MLCDT algorithm to pay heed to the relative weight and size of the different cost functions. It is in essence up the designer to normalize the cost functions and choose the relative weight coefficients. Figure 1 below depicts the functionality of the MLCDT algorithm

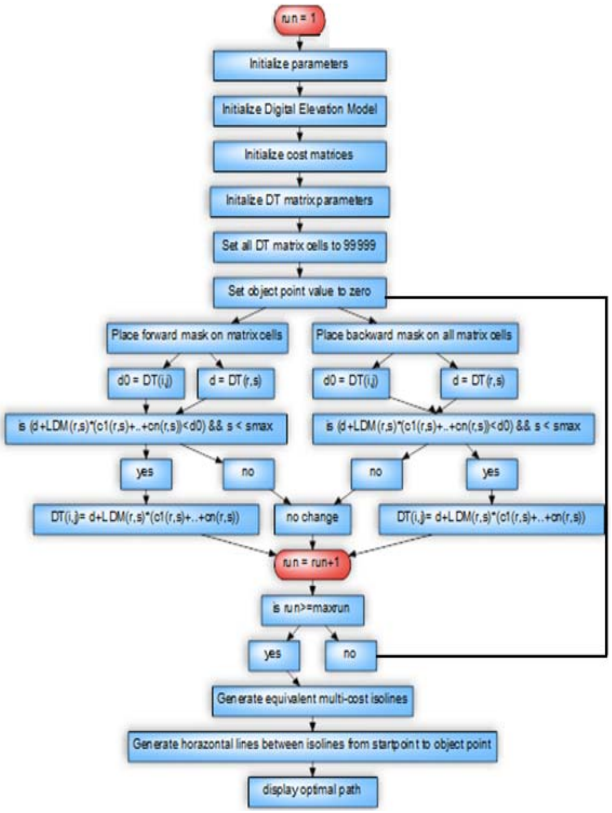

Figure 1 - MLCDT algorithm

SEPARATOR AND POWER PLANT LOCATIONS

The problem of obtaining the optimal location for separators and pipeline gathering points is essentially a Steiner problem. That is if incline, area costs and non-accessible areas are neglected, the problem becomes one of finding a point in a grid that has the smallest total distance to a number of predetermined points. A multiple weight distance transform algorithm can, as mentioned above, solve this problem. For each borehole a distance transform is computed and the resulting matrices are added with equal weight. The results of an unconstrained MWDT algorithm with 4 boreholes are displayed below. The dark blue area represents the recommended area for separator location.

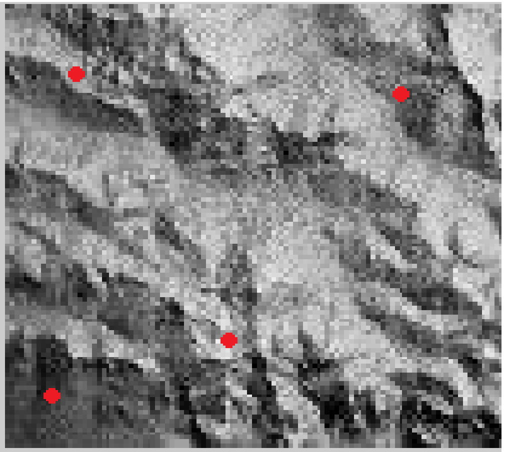

Figure 2 - MWDT example

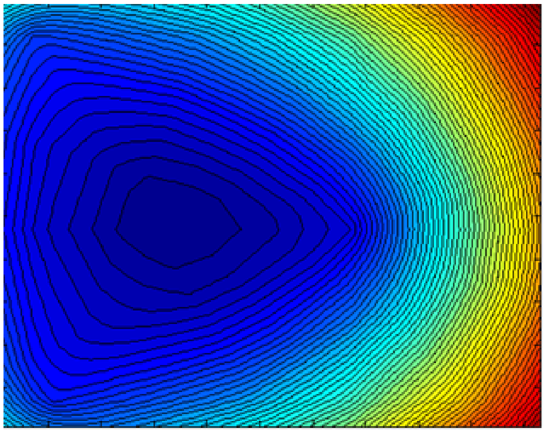

Figure 3 - Unconstrained MWDT results

The algorithm presented by this paper incorporates incline constraints and avoids placing separators and pipeline gathering points in non-accessible areas by using the previously presented algorithm to define the non-accessible areas. The results for the same area incorporating incline constraints and non-accessible areas are shown in figures 3 and 4

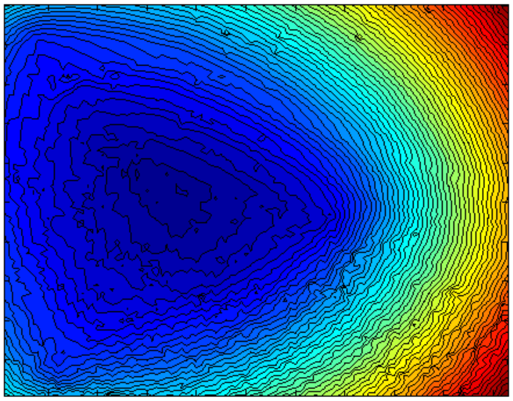

Figure 4 - Constrained MWDT results

DISTANCE TRANSFORM VISUAL EFFECTS RANKING

It is highly desirable to be able to obtain the optimal pipeline route with regards to visual effects. In order for this to be possible a logical first step is to obtain some sort of rank of the different locations in a geothermal area. In essence it is necessary before any optimal path algorithm is used on a DEM of a geothermal area to rank all the pixels with regards to the visual effects a pipeline in that location would cause. Distance transforms with their ability to register the shortest path from all points to the central point used in the transform present a very elegant way to achieve this. When a simple unconstrained distance transform is performed with only one object point, the shortest path from all points to this object points will be a direct line. That is, the shortest line registered by the DT algorithm is the line of sight. Since the DT algorithm registers all the points between the object point and a selected point, it becomes simple to obtain information about the properties of all the points between the selected point and the object point.

The proposed method of this paper is to calculate the DT for every point in the image, with regards to multiple selected points where it is desired to minimize the visibility of the pipeline (roads, houses, tourist sites, etc). Between each pixel and all the selected visibility test points, the DT algorithm records all the points in between. For each pixel the height of all the points between the pixel (object point) and the observation points is recorded. The height of the line of sight is then calculated and the algorithm calculates if at any point the line of sight from observation point to the object point is interrupted. If it is interrupted, that is if the object point is not visible from the observation point, the pixel gets a full score due to this observation point. If the line of sight is not interrupted the score of the point is proportional to the distance to the observation point. If it is farther away, the visibility declines and the score will be higher. The total score of each pixel is the sum of the score for this pixel due to each observation point.

When observing a pipeline from afar, it is clearly most visible when the line of sight is not interrupted and when the area behind the pipeline in the line of sight is clear, that is if the surface behind the pipeline is lower than the line of sight. The observer sees the pipeline much more clearly if only the horizon or some geographical formation a substantial distance away from the pipeline is viewed behind it. Indeed in the Icelandic geothermal industry today, engineers responsible for route design attempt to first of all hide the pipeline as previously explained, and second of all if this is not deemed practical, to make sure that behind the pipeline (in terms of the line of sight) is an obstacle that interrupts the line of sight. In the ranking method used by this paper this is incorporated. The algorithm for the ranking method then is:

```
$for\ i = 1\ to\ xdim$
  $for\ j = 1\ to\ ydim$
    $get\ DEM(i,j)$
    $for\ \ k = 1\ to\ NumObs$
      $[r,s] = ObPoint(k)$
      $get\ DEM(r,s)$
      $Dist = DT([r,s],[i,j])$
      $Route = calc.path\ from\ [r,s] to\ [i,j]$
      $SRoute =\ calc.\ line\ of\ sight\colon\ [r,s]\ to\ [i,j]$
      $if\ any\ (Route(l) \geq SRoute(l))$
        $rank(k) = \frac{10}{Numobs}$
      $elseif\ any(DEM(k\colon t) \geq SRoute(k\colon t))$
        $rank(k) = \frac{8}{Numobs}$
      $else$
        $rank(k) = 8 * \frac{Dist}{MaxDist} * \frac{1}{NumObs}$
      $end$
      $TotalRank(i,j) = sum(rank)$
    $end$
  $end$
```

Here "DEM(i,j)" represents a grid point value in the digital elevation model. "Dist" is the distance given by the simple distance transform. "ObPoint" is the object point matrix, which is the matrix of all observation points. "Route" is the path calculated by the simple distance transforms. "SRroute" is the calculated line of sight from observation point to grid point (i,j), "rank(k)" is the k-th element in the rank matrix for each grid point, "t" is the tolerance allowed for a obstacle behind the pipeline. "MaxDist" represents the maximum visible distance. "NumObs" the number of observation points. "Totalrank(i,j)" represents the (i,j) element of the resulting ranking matrix.

The algorithm is used on the sample area (figure 5) shown below. In this example the red line represents the observation line that is discretized into the observation points used in the algorithm. The results from this are shown below (figure 6)

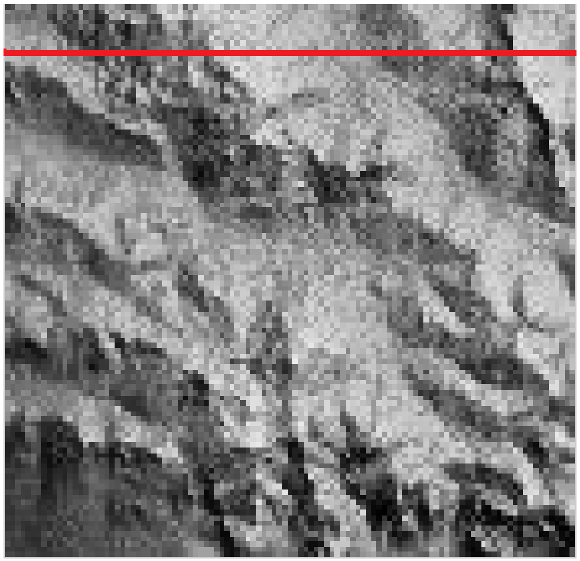

Figure 5 - Visibility ranking example

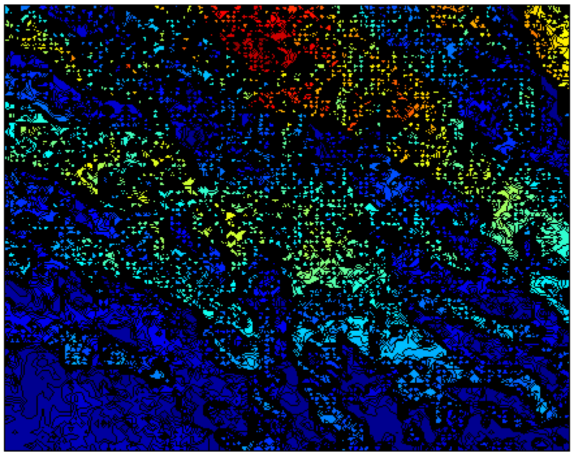

Figure 6 - Visibility ranking example results

CASE STUDY: HVERAHLÍÐ GEOTHERMAL POWER PLANT – OPTIMAL ROUTE WITH REGARDS TO VISUAL EFFECTS

Geothermal area features

To begin with the method is used to find the optimal route with regards to only the visual effects in the following example from the Hverahlíð geothermal area in Iceland (figure 7)

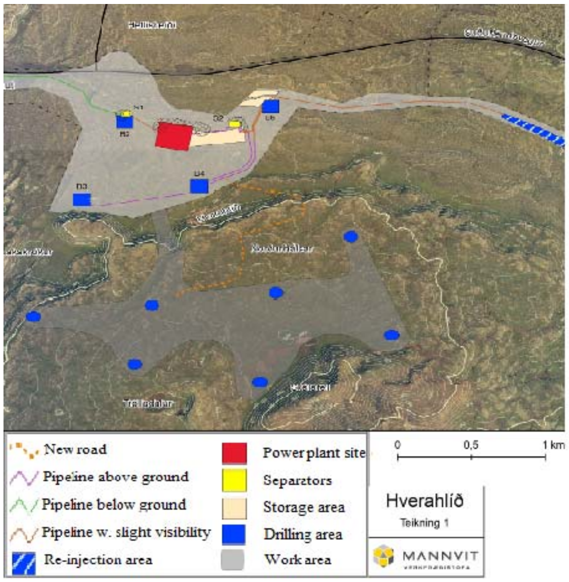

Figure 7 - Hverahlíð geothermal area

The problem as described by the company building and running the geothermal power plant at Hverahlíð, Reykjavík Energy (Orkuveita Reykjavíkur) is to find the optimal gathering point for all the boreholes on the upper platform and to then design the optimal route for the pipeline from the gathering point to the separator to the east of the power plant area. The route has the constraints of having a maximum downward incline of 5% and upwards of 0%.

MWDT gathering point selection

Following are the results of the MWDT gathering point selection for the boreholes. From this point the main pipeline will originate and it will end at the separator location shown in figure 7. The optimal gathering point is indicated by the red square in figure 8 below.

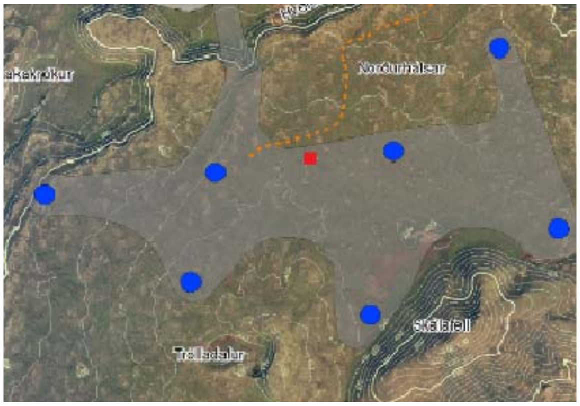

Figure 8 - MWDT gathering point selection

The results of the MWDT are displayed in the following image where as can be seen the area surrounding the immediate optimal gathering point is flat. This means that the gradient constraints do not have significant effects on the results, however as was seen in the previous MWDT example this is not always the case.

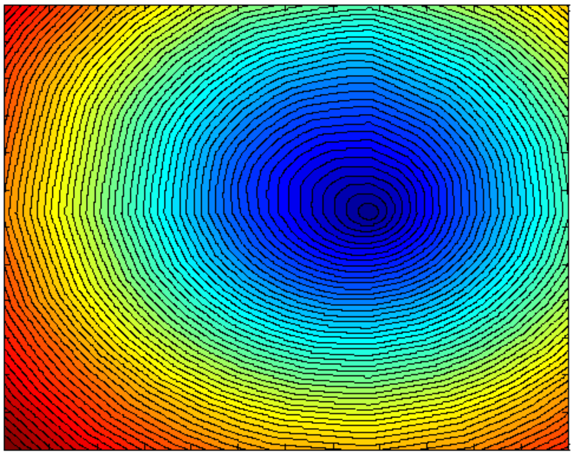

Figure 9 - MWDT of immediate area surrounding gathering point

Visual effects ranking

Following are the results of the distance transform ranking of the Hverahlíð geothermal area. In this example the road taken into consideration for visual effects is the main road shown in figure 10.

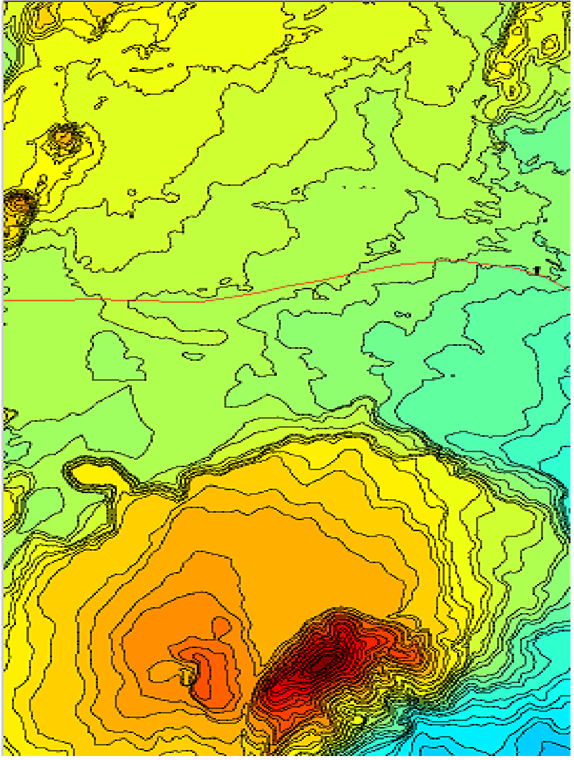

Figure 10 - Height isolines Hverahlíð

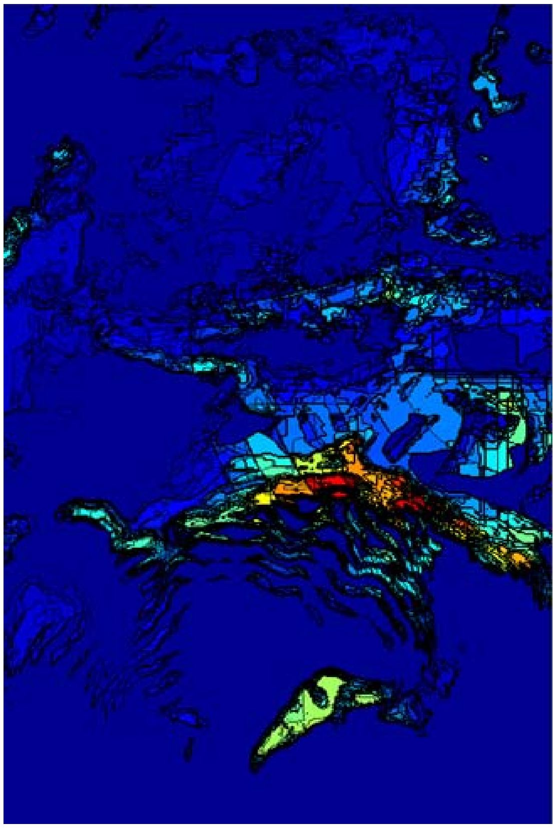

Figure 11 - Hverahlíð visual impact ranking results

In the results from the visual effects ranking shown above (figure 11), the scale is from dark blue (minimal visibility from all observation points), to red (high visibility from multiple observation points. As can be seen in the figure all points close to the road have rankings in the medium range, this is due to the fact that an object point close to the road will be seen by observation points close to that object point but not by observation points further away on the road. It is however desirable for the algorithm that points close to the road rank in the mediate range and not in the top range, becouse often it is neccesary for a pipeline to cross the road. The algorithm functions in such a way that the higher the ranking, the more unlikely it is to choose the path through the area. If the whole area adjacent to the road would be in the highest ranking range it would be impossible for the algorithm to cross a road. The ranking system employed ensures that the MLCDT algorithm is unlikely to choose a path close to a road (unless an obstacle ensures zeros visibility from the road) but can if forced choose a path crossing a road. The highest ranked areas in the example are the hills and mountain sides facing the road. These areas are be seen by most observation points on the road and are therefore highly unsuitable for pipeline placement. The best ranked areas are those where obstacles and distance ensure close to zeros visibility at their respective points.

Optimal path

Following are the results of employing the MLCDT algorithm on the visual effects ranking matrix previously obtained. The starting point for the algorithm is the optimal gathering point obtained previously and the object point (end point) is the separator adjacent to the proposed power plant site. In the following contour image of visual effects isolines, for clarity fewer isolines are shown than are used to obtain the final path.

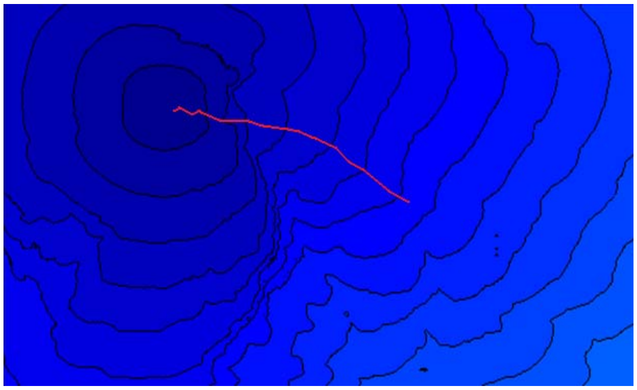

Figure 12 - Least visibility isolines

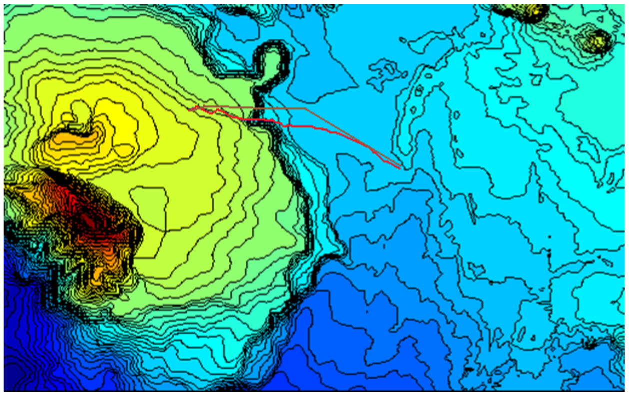

Figure 13 - Hverahlíð optimal path

In the following example one of the boreholes has been removed from the gathering point selection causing the gathering point to be selected to the northwest of the formerly proposed gathering point. In the following figures the effects of this on the least visibility isolines and the optimal path are displayed.

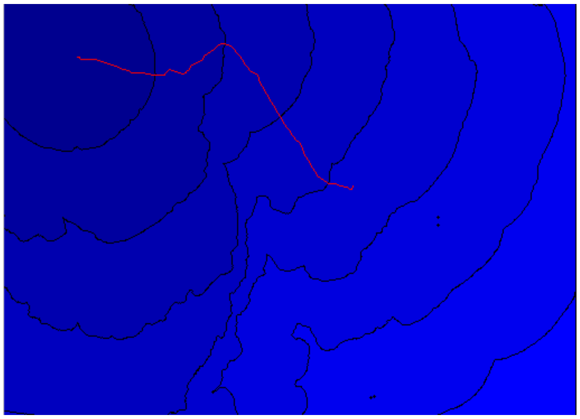

Figure 14 - Least visibility isolines with regards to second gathering point (figure display's only closest isolines)

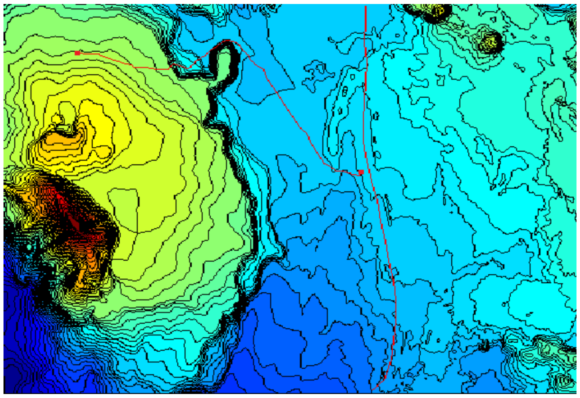

Figure 15 - Optimal path with regards to second gathering point

In figure 13 the red line depicts the route recommended by the MLCDT algorithm while the brown line depicts the approximate route proposed in the original planning for the area (the route follows the proposed work area in the approved preliminary plan for the area).

As can be seen in figure 13 the recommended route ascends up the hill through a valley which offers the aforementioned obstacles in the line of sight that are sought to minimize the visual impact of the pipeline. It differs from the originally proposed route in that it employ's the hills of the adjacent valley in order to minimize the visual impact.

In figure 15 the route proposed by the method for the second gathering point is depicted. Moving the gathering point slightly has caused the optimal route to change significantly, in this case the route proposed used the hill range extruding from the mountain to minimize the visual effects.

Multiple cost functions

In the following images the effects on the proposed route by using 2 cost functions are displayed. The first cost function is the previously obtained visual effects ranking and the second is a random matrix. In praxis this second matrix could represent anything from land cost to terrain quality.

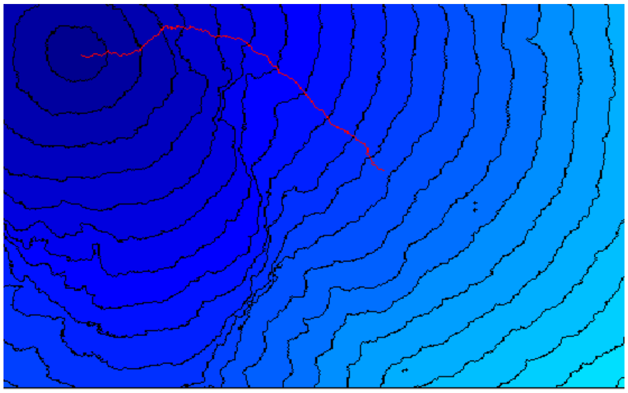

Figure 16 - Multiple cost isolines Hverahlíð

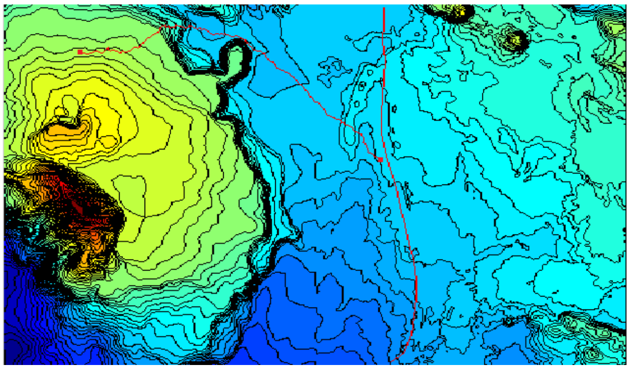

Figure 17 - Optimal route with regards to multiple cost functions Hverahlíð

Route\ranking	*% MLCDT*
MLCDT	-
Proposed	213
Shortest	482

Table 1 - Comparison of route visual effects

As can be seen in table 1 the visual impact of the proposed route is 213% of the visual impact of the proposed route (using the proposed ranking system and 32 observation points distributed evenly along the road). This is a significant difference especially given that the MLCDT route and the proposed route do not vary to a great degree. The visual impact of the shortest possible route within the incline constraints is 482% of the MLCDT visual impact.

MLCDT	-

Proposed	220
Shortest	456

Table 2 - Comparison of route visual effects for second gathering point

As table 2 shows the results for the second gathering point are comparable to those for the first gathering point. The shortest route using the proposed work area for the pipelines has a total visual impact rank 220% that of the route proposed by the method of this paper. Similarly the shortest possible route has 456% the visual impact of the proposed route.

Figure 17 displays the optimal route with regards to visual effects and the random matrix used as the second cost function. The values of the matrices are normalized but as previously mentioned the results obtained using this method are subjective due to their dependence on the user providing the relative weights of the cost functions. The proposed route with this method differs somewhat from the other routes previously shown and ascends up the hills at a more northerly location than both the other routes but still employs the extruding hill range to minimize the visual effects

CONCLUSIONS AND FURTHER WORK

The case study presented above shows that the method used in this paper, the improved algorithm and the ranking system introduced offer a good, functional way to design pipeline routes with regards to minimal visual impact. It also offers the possibility to design pipelines with regards to multiple criteria. The results show that method is successful in designing a route minimizing the visual impact of a pipeline while meeting design constraints.

As the case study above shows, a small variance in the route chosen can have a notable impact on the visual effects of the pipeline. Using this method, there is virtually no upper limit on the level of detail achievable designing the optimal route. The only limit is that of the resolution of the DEM used. In Iceland DEM's representing a majority of the country are available with a resolution of 25x25cm^2.

Proposed next steps in the development of this method are modifying it to take into account necessary expansion units for the pipeline and also to take into account the flow regime of the geothermal brine being transported. It is possible that the route resulting from this method would have to be modified to adequately design with regards to these objectives.

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