Optimum Topology, Route and Site Selection of a Steam System for Geothermal Power Plant

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***Abstract*—This paper proposes a new approach to select the location for separators, topology and routes for two phase flow pipelines in a geothermal steam gathering system using a weighted variable topography distance transform and evolutionary algorithm. A multiple weighted distance transform is presented and used to find the optimum location of site for a steam separator based on the flow capacity of geothermal wells. In order to minimize the pressure drop and the slug flow conditions in the pipeline, the routes are monotonic and the incline is slight. A map with weighted distance for eight wells shows the accessible area and the distance for the shortest legal route from each well is calculated. Based on the distance table and the cost of the pipe for different diameters the system is optimized using evolutionary algorithm. The optimum site location reduces the total pipe length from all wells by 4% and the topology optimization reduces the cost by 38%.**

***Index Terms*—Optimization, route selection, steam system, topology, weighted distance transform.**

I. Introduction

IN geothermal power plants, the steam system is a costly component of the infrastructure in terms of construction requirements. The steam system consists of geothermal wells, well head equipment, pipelines and separators. This paper describes an approach for optimum design of a steam system, with focus on topology and route selection for pipelines transporting two phase fluid from geothermal wells to a separation station and the optimum site selection of the station.

Geothermal power plants are often near tectonic plate boundaries placed in a rough and difficult volcanic landscape. Location of well platforms is based on geological and hydrological surveys and therefore the platforms are scattered around the reservoir area often with long distances between well sites. After drilling, each well is charged for testing and the production rate is estimated. Finding the optimum placement of the separator station and the optimum route for two phase flow pipelines from each well site to the separator station, for wells with different production capacity, can be a challenging process. Ad hoc methods are often employed based on designer's experience, maps of the area, graphical information systems and on-site surveying. The goal is to keep the pipeline route as short as possible and to minimize turns and incline. One of the constraints is to keep the route monotonic and the incline slight in order to minimize the pressure drop and the slug flow conditions in the pipeline.

Several traditional optimization techniques have been developed through the years for route selection but over the last ten years, meta-heuristic algorithms have been used more extensively. Genetic algorithms [1], particle swarm optimization [2], differential evolution, harmony search [3], intelligent water drops, evolution strategies, simulated annealing and ant colony optimization [4], have all been used for routing problems.

A digital elevation model (DEM) or a digital terrain model (DTM) is a digital representation of a ground topography and such models are available for the majority of Icelandic topography. DEM's are commonly constructed using remote sensing techniques and also by land surveying. With the increased availability of Digital Elevation Models (DEMs), a number of automated design processes have been introduced by Delavar, Naghibi and Douglas [5,6]. These methods work in conjunction with Geographic Information Systems and are often used to find the Least Cost Pathways.

Distance transforms (DT) is an image processing method for digital images. It was first introduced in the paper by Rosenfeld and Pfaltz [7]. The method calculates 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 Butt [8]. The Variable Topography Distance Transform (VTDT) introduced by Smith [9] offers a way to transform 3-D land surfaces to essentially open 2-D manifolds, which renders the use of a distance transform. The method offers a way to graphically determine the shortest and the least cost routes with gradient and curvature constraints along with inaccessible areas.

The use of Variable Topography Distance Transform has been proposed for geothermal pipelines in order to find the shortest route by Kristinsson et al. [10] and Kjaernesed et al. [11,12,13]. The method proposed in this paper extends this work by modifying the algorithm used and introducing a method for optimizing the topology and finding optimal

Manuscript received August 8th, 2016; revised August 11th, 2016. This work was supported in part by the University of Iceland.

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placement of separators by weighting the two phase flow from each well platform.

In literature, the topological optimization problems are often solved with either enumerative methods or heuristic methods. Some of the enumerative methods that are commonly used are Branch and Bound, Spanning Trees, Shrink and Search algorithm. The enumerative methods are often applied to small networks, but for larger networks the heuristic methods such as Simulated Annealing, Artificial Neural Network, Genetic Algorithm, are more often used because of their ability to find near global optimal solutions in a reasonable time. A study of literature shows that the genetic algorithm is used to solve many NP-hard discrete engineering problems as well as many optimization problems with large, complex search spaces [14, 15, 16].

The variable topography distance transform is described in section 2 and the case study designing a pipe distribution network for a steam field is presented in section 3. In section 4, the cost and the distances for legal routes are used with evolutionary algorithm to optimize the topology of the system. The paper concludes with a general discussion and a summary.

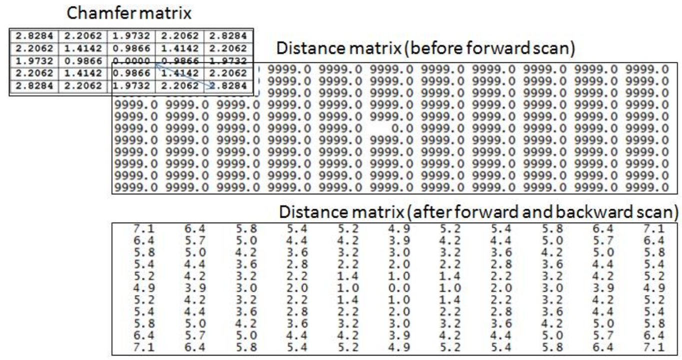
II. Multiple weighted distance transform

The Distance Transforms method is originally an image processing tool used on binary or gray-scale pictures. For an image, the method assigns each pixel with the distance to the nearest object pixel. The result is a new image that is a distance representation of the original picture. Calculating distances over 3-D surfaces can be difficult and computationally intensive. The Variable Topography Distance Transform (VTDT) introduced by Smith offers an approach to address this problem. The 3-D land surfaces are essentially open 2-D manifolds and with rendering the use of a distance transform is possible [9]. Rather than calculating the Euclidian distance to the object pixel, a Chamfer distance metric is used to approximate the distance.

When calculating a distance transform for a distance matrix, the values of the object points are set to zero, $d_0 = 0$ and all other points are set to a large number as shown in Fig. 1. The next step is to place the chamfer mask over each cell and map the value of the distance to the nearest object point to each grid point using the Bellman's equation,

$$d_{i,j} = min(d_{i+m,j+n} + c_{m,n}, d_{i,j}) \quad \text{for } i,j = 1,....,n \text{ and } m,n = -2,-1,0,1,2 \tag{1}$$

where $d_{i,j}$ is the value of the distance matrix at the central point of the chamfer mask, $d_{i+m,j+n}$ is the value of the distance matrix at the same location from the central point as $c_{m,n}$ is placed in the chamfer matrix. Both a forward and a backward scan are required. The metric used in this study is a 5x5 fractional chamfer as shown in Fig. 1



Chamfer matrix

2.8284	2.2062	1.9732	2.2062	2.8284
2.2062	1.4142	0.9866	1.4142	2.2062
1.9732	0.9866	0.0000	0.9866	1.9732
2.2062	1.4142	0.9866	1.4142	2.2062
2.8284	2.2062	1.9732	2.2062	2.8284

Distance matrix (before forward scan)

			9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
			9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
			9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	0.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0
9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0	9999.0

Distance matrix (after forward and backward scan)

7.1	6.4	5.8	5.4	5.2	4.9	5.2	5.4	5.8	6.4	7.1
6.4	5.7	5.0	4.4	4.2	3.9	4.2	4.4	5.0	5.7	6.4
5.8	5.0	4.2	3.6	3.2	3.0	3.2	3.6	4.2	5.0	5.8
5.4	4.4	3.6	2.8	2.2	2.0	2.2	2.8	3.6	4.4	5.4
5.2	4.2	3.2	2.2	1.4	1.0	1.4	2.2	3.2	4.2	5.2
4.9	3.9	3.0	2.0	1.0	0.0	1.0	2.0	3.0	3.9	4.9
5.2	4.2	3.2	2.2	1.4	1.0	1.4	2.2	3.2	4.2	5.2
5.4	4.4	3.6	2.8	2.2	2.0	2.2	2.8	3.6	4.4	5.4
5.8	5.0	4.2	3.6	3.2	3.0	3.2	3.6	4.2	5.0	5.8
6.4	5.7	5.0	4.4	4.2	3.9	4.2	4.4	5.0	5.7	6.4
7.1	6.4	5.8	5.4	5.2	4.9	5.2	5.4	5.8	6.4	7.1

Fig. 1. Chamfer matrix and distance matrix before and after one forward and backward scan. The object point is in the middle of the distance matrix.

When designing a two phase flow pipelines, there is a constraint on the gradient; the route should be monotonic and the incline should be slight in order to minimize pressure drop and slug flow conditions in the pipeline. Gradient and curvature constraints along with inaccessible areas are implemented in the algorithm using DEM. A DEM is a 2-D matrix where each element H_{ij}, represents the height in the corresponding surface location (i,j). With VTDT the gradient constraint is implemented in the regular Distance Transform by the condition:

$$\begin{aligned} &if(H_{i+m,j+n} - H_{i,j} < \Delta H_c \text{ and } \alpha_{i+m,j+n} < \alpha_c) \\ &\text{then } d_{i,j} = min(d_{i+m,j+n} + c_{m,n}, d_{i,j}) \\ &\text{else } d_{i,j} = d_{i,j} \end{aligned} \tag{2}$$

where the height, $H_{i+m,j+n}$ and the slope, $\alpha_{i+m,j+n}$ is calculated from the altitudes of the cells in question, from the DEM. The critical values of height difference, ΔH_c and slope, α_c, are user defined. Depending on the topology and the severity of the gradient constraint, some parts of the area covered by the DEM may be inaccessible, that is, no path bounded by the gradient constraints can reach there and the values of the VTDT matrix will not change.

Smith introduced the Multiple Weight Distance Transforms (MWDT) an algorithm that utilizes many distance transforms, each with weighted distance to relative importance [10]. The purpose is to find an area with a minimum distance with regard to different criteria. In the formulation presented here the distance transform is weighted with the flow condition or fluid capacity from each well platform. The MWDT matrix becomes,

$$D = \sum_k w_k \, DT_i\{A_k\} \tag{3}$$

where $DT_i\{A_k\}$ is a distance transform of type i to an object set $\{A_k\}$ and w_k is the weight factor. Each element in the matrix is defined by,

$$\begin{aligned} &if(\ (d_{i,j})_k = d_0 \text{ or } D_{i,j} = d_0 \text{ then } D_{i,j} = d_0 \\ &\text{else } D_{i,j} = D_{i,j} + w_k(\ d_{i,j})_k / m \text{ for } k = 1, m \end{aligned} \tag{4}$$

where w_k is the weight coefficient for the matrix number k and m is the total number of matrices.

Handling land-use constraints in MWDT, such as maximum allowable gradient, curvature or do-not-enter areas, is straightforward to implement as shown. All cells have heights (altitudes) assigned to them and these values are used to calculate the length between the cells in a 3-D space utilizing slope distance. With all these constraints taken into account, the MWDT method can find the shortest route satisfying the design values.

III. Route Selection and Steam Separators

A schematic diagram in Fig. 2 shows a single flash geothermal power plant system. A reservoir is a hot rock and a fluid that is used to transport the heat from the earth through wells to the ground. The fluid is often single phase in the reservoir at the depth of 2000 to 3000 m due to high pressure but it becomes two phase fluid at the well head. The two phase fluid is transported using pipelines from the well head or the well platforms to the separation station. At the separation station the steam is separated from the water phase and transported with a single phase steam pipeline to the turbine. The water is then transported from the separator with a reinjection pipeline to the reinjection wells often located at the boundary of the reservoir.

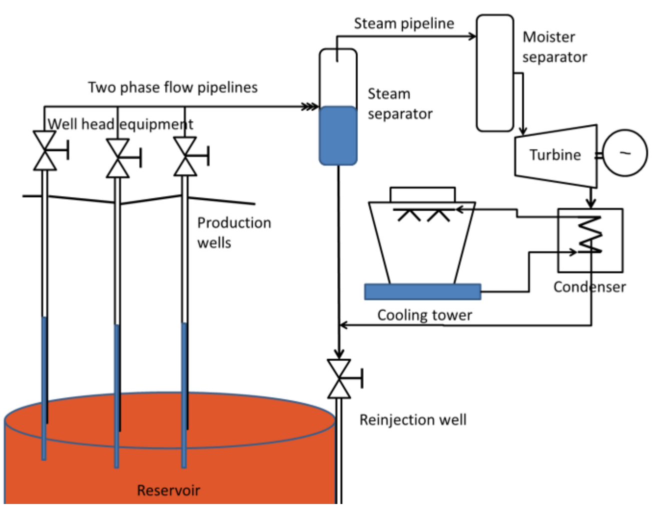


Fig. 2. Single flash geothermal power plant.

The location of the well platforms is based on geological and hydrological surveys and they are scattered around the reservoir area often with long distances between sites. After drilling each well is charged for testing and the production rate is estimated. Then the objective is to find the optimum placement of the separator station and the optimum routes for the two phase flow pipelines from each well site to the separator station. In this analysis, the optimization is based on wells with different production capacity as shown in Fig. 3. The eight wells have production capacities ranging from 38 kg/s to 86 kg/s with similar quality of steam and are planned to be used for production of 100 MW of electricity. A digital elevation model with the eight well platforms WP-11, WP-12, WP-13, WP-20, WP-21, WP-22, WP-23 and WP-24 with the location for the separator SP-SD is shown in Fig. 4. The separator SP-SD is located on a legal area with the shortest total length based on straight distance to each well.

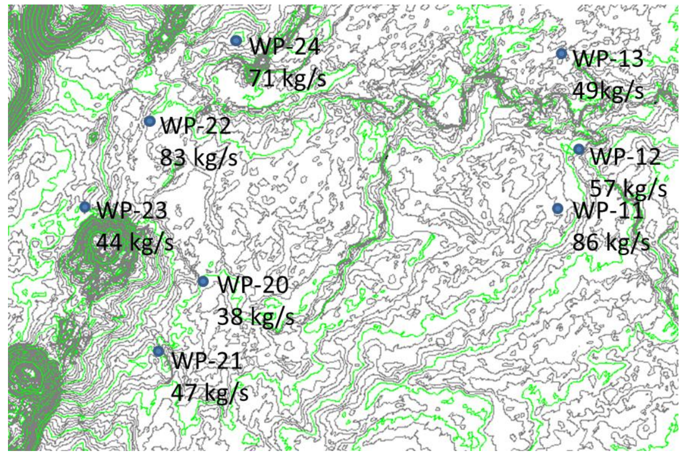


Fig. 3. Iso-lines showing height contours of a geothermal area with five production wells.

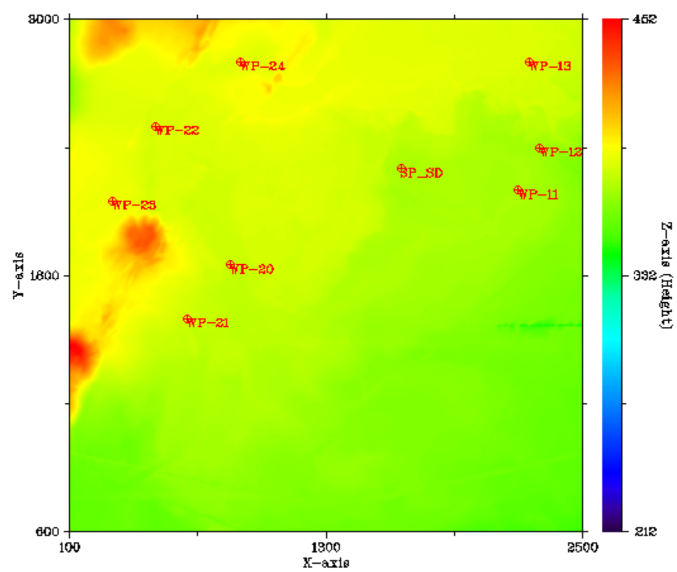


Fig. 4. A digital elevation model for a geothermal area, the location of the separator station, SP-SD is with shortest direct distances to all wells. The color shows the height contour of the landscape.

In figure 5, the results of MWDT for the wells and the shortest route with a monotonic pipeline to the separator SP-SD are shown. Eq. 2 returns untrue for the white area, or no route for monotonic pipeline or pipe with unidirectional slope can lie through that area from the wells being assessed. The equation therefore ensures that the gradient of the shortest route is within the desired value. The total length of the pipe system is 10301 m for the location SP-SD. Using the weighting process according to Eq. 3, the color shows the weighted distance from all wells with weights based on different flow rates the and the red box shows the optimum location based on weighted distance.

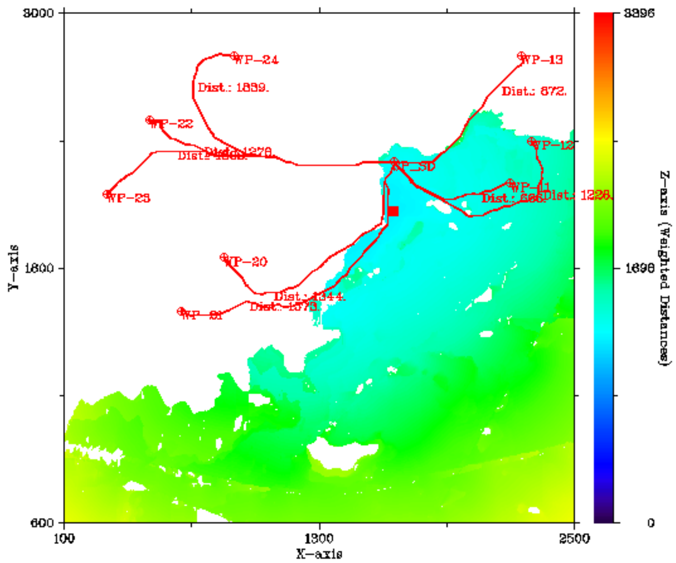


Fig. 5. Weighted distance map for the wells and routes to a separator located with shortest length based on straight distance to all wells. No access is through the white area with a monotonic pipeline, considering all wells. For this location the total length of the pipe system is 10301 m.

Fig. 6 shows the weighted distance map and the routes to the optimum location of the separation station or the red box. Compared to the location SP-SD, with the total length of the pipe system as 10301 m, the optimum weighted distance location of the separator at SP-OP as shown in Fig. 6 will have the total pipe length as 9864 m reducing the total length by 4%. The cost of the pipe system is reduced more as the length of pipes with the largest diameter is shortened due to the weighting process of the flow rate.

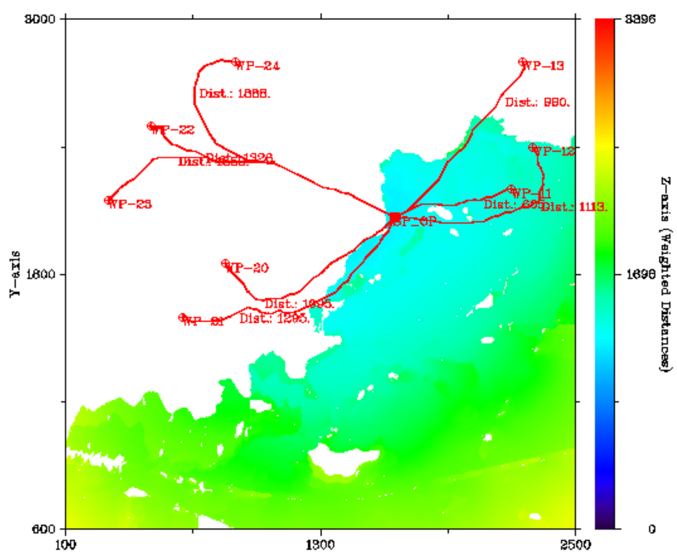


Fig. 6. Route selection for an optimum location of the separator based on weighted variable topography distance transform. The total length of the pipe system for this location is 9864 m.

IV. TOPOLOGY DESIGN AND DIAMETER OPTIMIZATION

A distribution network can be modeled as an undirected graph G(V, E) having node set V as vertices and link set E as elements. The network of steam pipe lines from well platforms to the separator can be classified as a static problem, dealing with topology, capacity and static flow rate. The objective function (5) is assumed to be the cost function of the pipe arrangement. The cost c_{pi} given in Table 1. includes the cost of pipes, bends, anchors, supports and construction. Distance table base on the weighted distance transform as shown in figure 6 is given in Table 2. The objective function or the total capital cost becomes,

$$f(O_{t1}, \ldots.O_{tN}, I_{f2}\ldots.I_{fN-1},I_{D1},\ldots I_{DN}) = \sum c_{pi} L_i \quad (5)$$

where the decision variables are, O_{t1} number of the placement that the pipe no. 1 goes to and I_{f2} is the number of placement that the pipe no. 2 goes from. Pipe no. 1 always goes from the separator station. The diameter variable, I_{Di} is an integer index to the diameter in Table 1. and the optimum value is based on the velocity constraint. The maximum allowable velocity of a steam in a pipe to avoid erosion is 30 m/s.

TABLE I.
STEEL PIPE SIZES WITH NOMINAL DIAMETER, PIPE THICKNESSES, INNER DIAMETER AND PRICES AS USD PER METER.

DN	200x4,5	250x5,0	300x5,6	350x5,6	400x6,3	450x6,3	500x6,3	600x7,8
Di [m]	0,2101	0,2630	0,3118	0,3444	0,3938	0,4446	0,4954	0,594
Cpi [$/m]	49,5	68,8	91,2	100,7	129,5	146,1	162,7	241,5

The main property of Genetic Algorithms (GA) is the population search where individuals store the decision variables in a coded representation corresponding to chromosomes in biology. A general order based GA is shown in Fig. 7. For combinatorial problems a common representation of the design variables is integer or permutation based. A commonly used selection method for GA is the tournament selection. In this selection method, a number of n-individuals are chosen randomly from the population and the best individual from the group is copied to the intermediate population. This is repeated as often as the number of individuals in a generation. The size n is called the tournament size. Increasing the tournament size results in a loss of diversity and increasing selection intensity. The permutation offsprings are created with an Edge recombination and the iterated Lin-Kernighan is used for mutation.

TABLE II.
DISTANCE BETWEEN WELL PLATFORMS AND SEPARATION STATIONS (M)

	Sep	WP11	WP12	WP13	WP20	WP21	WP22	WP23	WP24
Sep	0	999999	999999	999999	999999	999999	999999	999999	999999
WP11	605	0	999999	999999	999999	999999	999999	999999	999999
WP12	1113	381	0	999999	999999	999999	999999	999999	999999
WP13	990	704	327	0	2551	2998	2627	999999	999999
WP20	1095	1738	999999	999999	0	392	999999	999999	999999
WP21	1295	1891	999999	999999	403	0	999999	999999	999999
WP22	1326	2030	999999	999999	834	1220	0	999999	999999
WP23	1552	2255	999999	999999	712	1076	402	0	999999
WP24	1888	2591	999999	999999	1538	2051	940	999999	0

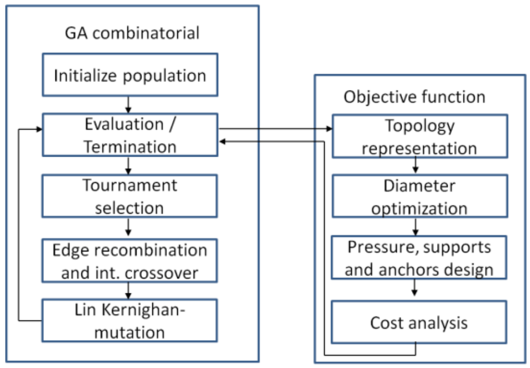


Fig. 7. GA for combinatorial problems.

The cost of the pipe arrangement as it is shown in Fig. 7. according to Table III, is 646 thousand USD and the total length is 9864 m.

TABLE III. LENGTH AND COST OF THE PIPE ARRANGEMENT AS IT IS SHOWN IN FIGURE 6.

		Total	SEP-WP20	SEP-WP22	SEP-WP11	SEP-WP24	SEP-WP23	SEP-WP13	SEP-WP21	SEP-WP12
Length	*Li* [m]	9864	1095	1326	605	1888	1552	990	1295	1113
DN			200x4,5	300x5,6	300x5,6	250x5,0	200x4,5	250x5,0	200x4,5	250x5,(
Vel.	*V* [m/s]		23,7	23,5	24,4	28,3	27,5	19,5	29,3	22,7
Cost	T USD	646	54	121	55	130	77	68	64	77

TABLE IV. LENGTH AND COST OF THE PIPE ARRANGEMENT AS IT IS SHOWN IN FIGURE 6.

		Total	SEP-WP20	SEP-WP22	SEP-WP11	WP22-WP24	WP22-WP23	SEP-WP13	WP20-WP21	WP11-WP12
Length	*Li* [m]	6142	1095	1326	605	940	402	990	403	381
DN			350x5,6	450x6,3	400x6,3	250x5,0	200x4,5	250x5,0	200x4,5	250x5,0
Vel.	*V* [m/s]		19,7	27,6	25,4	28,3	27,5	19,5	29,3	22,7
Cost	T USD	581	110	194	78	65	20	68	20	26

Fig. 8 shows the optimum arrangement or topology of the pipe system with the blue lines. The cost of the system reduces from 646 T-USD to 581 T-USD and the total length of the system is 6142 m.

Compared to the price that was reduced by 10%, the total length of the system was reduced from 9864 m to 6142 m or by 38 %.

V. CONCLUTIONS

This paper shows how the Multiple Weight Distance Transform method can facilitate the route design process for pipes carrying two-phase geothermal fluid, giving the user the ability to get a clear map of accessible area and detailed results of shortest pipe routes from wells to separator stations. By utilizing highly accurate digital maps the system can compare different routes, each with its own set of design- and environmental constraints, very quickly and efficiently. Results show how the method can reduce the total length of pipes from eight well platforms to one separator station by 4% and by adding an evolutionary algorithm for topology design the cost is reduced by 10% and the total length by 38 %. This level of automation is a change from the route design process today, which relies on ad hoc methods and on-site studies. The method also gives a platform for formalizing both internal knowledge and design experience.

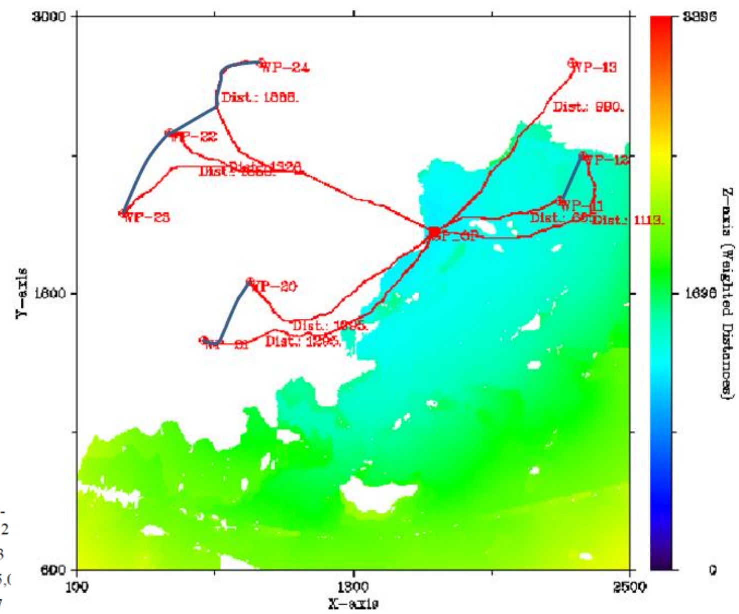


Fig. 8. Route selection for an optimum topology of the pipe system and the placement of the separator based on weighted variable topography distance transform and evolutanry optimization shown by blue lines.

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