

Biologically Inspired Optimization of Building District Heating Networks

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Abstract

*In this paper we show that a biologically inspired model can be successfully applied to problems of building optimal district heating network. The model is based on physiological observations of the true slime mold *Physarum polycephalum*, but can also be used for path-finding in the complicated networks of mazes and road maps. A strategy of optimally building heating distribution network was guided by the model and a well-tuned ant colony algorithm and genetic algorithm. The results indicate that although there are not large-scale efficiency savings to be made, the biologically inspired amoeboid movement model is capable of finding results of equal or better optimality than a comparable ant colony algorithm and genetic algorithm.*

Keywords: amoeboid movement model, complex network, ant colony algorithm, heating network optimization

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1. Introduction

District heating networks (DHN) serve to transport hot water or steam from treatment works to individual customers and usually represent a significant capital investment in the development of the urban environment [1].

The problem of designing a DHN to optimally meet performance criteria on one hand, such as delivering sufficient water pressure for high rise buildings and fire fighting; whilst minimizing cost criteria, such as the cost of material, excavation, frequency of maintenance is known to be NP hard [2]. On the other hand, the environment is becoming an increasingly important in the philosophy of the modern society, and internationally people have become more aware of the environment, and the consequences of global warming [3]. To consider the growing demands for a reduction of the CO₂ emissions, and the government's requirements on the district heating to operate with a greener profile, proposal for optimization of the supply of district heating network was proposed in this paper.

In the past decades, a large variety of computational algorithms have been devised for this task which include well known techniques in operational research such as linear, dynamic and integer programming. In recent years however, a variety of nature-inspired and meta-heuristic algorithms such as genetic algorithms, simulated annealing and tabu search [4] have been widely investigated as useful research tools for DHN design. Amongst meta-heuristic algorithms aforementioned, ant colony algorithm (ACOs) [5] has been generally accepted to be one of the most successful solutions for DHN optimization [6]. Whilst ACOs have provided good solutions to heating distribution optimization problems for some time, the steady increase in the complexity of the network information being kept by the heating companies means that ACOs are no longer always suitable. This is in part due to the long running times incurred by the algorithm due and in particular, the high number of objective function evaluations required by evolutionary techniques. An increasing number of elements in the network and more detailed 24-hour simulation studies have seen the complexity of a single network simulation increase massively. Therefore, scientists are constantly looking for techniques which might deliver ACO-class results, but with fewer objective function calculations.

The optimization of DHN has two criteria: 1) the new method should be guaranteed to find the shortest route. That means stochastic based processes are out of consideration; and 2) the new algorithms should be capable of flexible adaptability and re-routing. In recent years,

scientist find a completely new method that fulfills these criteria is demonstrated using a mathematical path finding model derived from observation of an amoeboid organism, the true slime mold [7].

In this paper we investigate the application of an amoeboid movement model to solve the problem of DHN optimization. We describe the application of the true slime mold systems to a district heating network and compare it with a well-tuned ant colony algorithm, with mixed results. The remainder of this section discusses heating distribution network optimization and previous research into using biologically inspired approaches to this purpose.

2. Method

DHNs are part of the energy supply system, comprising of number of interconnected elements such as pipes, nodes, pumps, valves, and reservoirs of varying shapes and sizes. The nodes represent combined points of heading demand (e.g. housing or industrial estates) on the system. The purpose of the network is to deliver hot water or steam to the demand nodes from the heating treatment works or other source throughout the day and under varying demand conditions.

There are many options to be considered when optimizing a DHN, but in most case, an existing network is already in place making it difficult to attempt major structural change in the existing design. Changing the position of the network elements is considered a major structural change and would be very costly. As this is a large capital investment and maybe there is some energy waste after use, the heating companies inevitably want modifications to last for long time periods, typically 50-100 years. Therefore, optimization should be considered and implemented before construction.

The plasmodium of true slime mold *Physarumpolycephalum* can tackle a maze and some other types of geometrical puzzle, and can successfully optimize survival tasks [8]. The challenge is to extract a mathematical algorithm for this natural computation. The body of the plasmodium contains a network of tubes, which enables nutrients and chemical signals to circulate through the organism. When food sources are presented to a starved plasmodium that has spread over the entire surface of an agar plate, parts of the organism concentrate over the food sources and are connected by only a few tubes. The path connecting these parts of the plasmodium are the shortest possible, even in a maze [9]. The physiological mechanism of tube formation has been established: tubes thicken in a given direction when shuttle streaming of the protoplasm persists in that direction for a certain time [10]. This implies positive feedback between flux and tube thickness, as the conductance of the sol is greater in a thicker channel.

We now demonstrate the application of our model to DHN design. Grey background and white lines in Figure 1 show the street structure (network) of west district of a Chinese city. Blue, green and yellow rectangles represent apartments (sink nodes) with different demands of energy. We use this map as maze in the model of plasmodium of true slime mold *Physarumpolycephalum*. The optimized shortest and the most efficient heating network will be fund by the organism.

In this case, we use pattern recognition techniques to obtain street and apartment blocks. To do so, it is necessary to possess the node data, in which each node corresponds to a junction in the street network, and the node connection data that correspond to the distances (or cost) between connected nodes. Once the data are set by selecting the source node and all the sink nodes, it is easy to obtain the optimized network using *Physarum* solver.

We developed a mathematical model for adaptive network construction to emulate *Physarum* behavior, based on feedback loops between the thickness of each tube and internal protoplasmic flow in which high rates of streaming stimulate an increase in tube diameter, whereas tubes tend to decline at low flow rates. The initial shape of a plasmodium is represented by the map with objects being extracted. The edges represent plasmodial tubes in which protoplasm flows, and nodes are junctions between tubes. Suppose that the pressures at nodes i and j are p_i and p_j , respectively, and that the two nodes are connected by a cylinder of length L_{ij} and radius r_{ij} . Assuming that flow is laminar and follows the Hagen-Poiseuille equation, the flux through the tube is:

$$Q_{ij} = \frac{\pi r_{ij}^4 (p_i - p_j)}{8 \delta L_{ij}} = \frac{D_{ij} (p_i - p_j)}{L_{ij}}$$

Where δ is the viscosity of the fluid, and $D_{ij} = \Pi r^4 / 8\delta$ is a measure of the conductivity of the tube. As the length L_{ij} is a constant, the behavior of the network is described by the conductivities, D_{ij} , of the edges.

3. Results

We observed Physarum connecting a template of 42 nodes that represented geographical locations of apartment in the west part of the city. The Physarum plasmodium was allowed to grow from source node and initially filled much of the available land space, but then concentrated on apartments thinning out the network to leave a subset of larger, interconnecting tubes. The result is shown in Figure 1. Red lines show that possible connections between nodes.

In Figure 2 Amoeboid and GA are both run for 300 000 fitness evaluations. Amoeboid continues to evolve the quality of solutions until over 200 000 fitness evaluations and shows evidence of further improvement. On the final iteration performed by Amoeboid the difference between the fitness of the iterations best solution $f(S_{ib})$ and the mean average fitness of solutions $f(\Phi)$ was 921,083,790. The difference between the $f(\Phi)$ and $f(S_{ib})$ indicates that further improvement on the quality of solutions could be achieved given more fitness evaluations as close $f(\Phi)$ and $f(S_{ib})$ values indicate that stagnation is occurring. Whereas the greater the difference between $f(\Phi)$ and $f(S_{ib})$ the more exploration is being conducted. Amoeboid appears to be the algorithm of choice here as it has achieved a much fitter solution than ACO. GA improves the quality of solutions slower than the Amoeboid and provides a less fit final solution and therefore is poorer in both respects. Amoeboid has achieved a fitter final solution than the GA which requires more fitness evaluations than both the Amoeboid and the ACO.



Figure 1. Street Structure and Optimized Heating Network

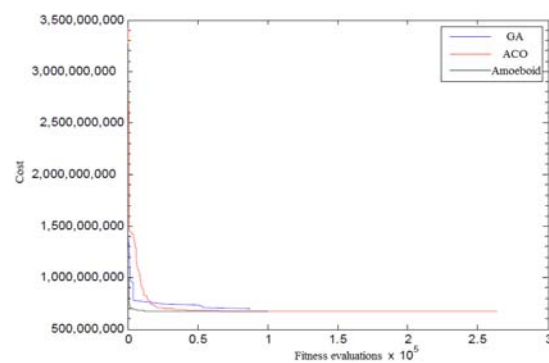


Figure 2. Comparison of Cost among Three Algorithms: genetic algorithm (GA), Ant colony optimization (ACO) and the Amoeboid solver

4. Conclusion

Overall, we conclude that the Physarum networks showed characteristics similar to those of the real heating networks in terms of cost, transport efficiency, and fault tolerance. However, the Physarum networks self-organized without centralized control or explicit global information by a process of selective reinforcement of preferred routes and simultaneous removal of redundant connections.

Acknowledgement

This work was supported in part by a grant from College and University Nature Science Foundation-Funded Project of Anhui Province, China (No. KJ2012B170 and No. KJ2013B248).

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