Noisy Genetic Algorithm for Stochastic, Time-Varying Minimum Time Network Flow Problem

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A metaheuristic based on principles of noisy genetic algorithms is proposed to address the minimum time network flow problem, in which arc traversal times and capacities are random variables with time-varying distribution functions. A specialized encoding scheme exploits the problem's structure. To assess the fitness of solutions at each generation, multiple sampling fitness evaluations are considered. A stratified sampling technique is used in the selection of sample sets for this purpose. Such an approach ensures that scenarios with low probability but high consequence are taken into consideration in evaluating possible solutions and simultaneously accounting for the low likelihood of such events. This work has application in many arenas but was motivated specifically by the need to determine optimal instructions for the evacuation of a geographic region, building, or other large structure in the event of circumstances warranting quick escape.

This paper addresses the problem of determining the set of paths along which to ship supply from a source to a sink such that the total time required to complete all shipments is minimized in a stochastic, time-varying (STV) capacitated network, in which arc traversal times and capacities are random variables with time-varying distribution functions. The problem is referred to here as the minimum time network flow problem (MTNFP) in STV networks. In this problem, supply may arise over time, but waiting is not permitted at intermediate nodes. That is, solutions may not suggest that a unit of flow wait while en route to the destination, as might be beneficial if travel times improve over time (i.e., if the network is non–first in, first out). Flow is permitted to move dynamically through the network, allowing capacities to be recaptured over time. This work has application in many arenas, but was motivated specifically by the need to determine optimal instructions for the evacuation of a geographic region, building, ship, or other large structure in the event of military attack, fire, natural disaster, chemical attack, discovery of hazardous materials or biological agents, or other circumstances warranting quick escape with limited notice.

Numerous efficient algorithms exist in the literature for determining optimal solutions to network flow problems that arise in many industries [see Ahuja et al. for additional detail on network flow problems and related solution techniques (*1*)]. However, nearly all of these works address problems with deterministic and time-invariant characteristics. In real-world applications, however, arc attributes (e.g., arc traversal times and capacities) typically vary over time. In the context of emergency evacuation, such time variability occurs because conditions worsen over time and vehicular or pedestrian traffic or both often increase as more people decide to evacuate, before subsiding once the evacuation nears completion. Numerous works explicitly consider the dynamic nature of network attributes, in which flow moves dynamically through the network over time and arc capacities are recaptured over time as the flow moves out of the arcs (*2, 3*). Few works have considered arc traversal times, capacities, and supply at the source to be time-dependent (*4–6*). Chen and Miller-Hooks revisit this problem to formulate the building evacuation problem with shared information (*7*). Their formulation ensures that evacuees departing from an intermediate or source location at a mutual point in time receive common instructions.

Furthermore, future values of such attributes cannot be known a priori with certainty. In evacuation networks, arc traversal times and capacities depend on conditions that arise as a consequence of one or more random events. Within the context of evacuation, the level of impact on the network will depend on the location and intensity of the event and external conditions that affect damage propagation (e.g., fire spread). The impact of such an event, therefore, cannot be known a priori, and likely it will not be possible to assess near-term conditions with certainty immediately following the event, even if the nature of the event is known precisely. Existing approaches proposed in the literature to solve related network flow problems generally do not explicitly model the variable and uncertain conditions inherent in, for example, circumstances warranting emergency evacuation.

Several researchers have addressed stochastic but static flow problems in the form of network connectivity and reliability, in which the nodes or arcs may randomly fail with known probability [e.g., Frank and Gaul (*8*) and Lin (*9, 10*)]. Another approach for examining the performance of capacitated networks with random arc failures is to consider the expected value of maximum flow. Because computing such an expected value is NP-hard [as mentioned in, for example, Nagamochi and Ibaraki (*11*)], upper and lower bounds on the expected maximum flow are used as an approximation to the exact value. The expected value of the maximum flow can be used only in the evaluation of network performance; that is, no routing plans are developed.

Other works have addressed stochastic network flow problems, in which routing plans are determined. Talebi and MacGregor Smith modeled the minimum expected evacuation time problem given time-invariant network attributes with analytical queuing network models

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