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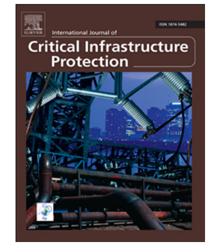

A length-based, multiple-resource formulation for shortest path network interdiction problems in the transportation sector

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ABSTRACT

This paper analyzes a variation of the shortest path network interdiction problem for homeland security scenarios pertaining to attacks on critical infrastructure and key resources that use highways in the transportation sector as conduits for gaining proximity to targets. The model represents a static Stackelberg game and may be formulated as a bi-level mixed integer program with two players: an attacker and a defender. Using highway segments as arcs, a set of predetermined highway entry points and a target set, the attacker seeks the path of maximum non-detection between any entry and target node. The defender impacts the minimum value of this maximum non-detection path through the allocation of a limited number of defense sensors that reduce the non-detection probabilities for arcs that fall within the range of influence of a sensor. Two types of sensors, static and dynamic sensors, are available to the defender and separate influence functions model their respective effects on arc non-detection. A geographic information system is used to collect, store and process network information and sensor influence information stored in a relational database. The results of the problem formulation are analyzed in a case study involving a California highway sub-network. The case study also examines the effects of sensor parameters, budget levels and target sets on the solutions that are obtained.

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1. Introduction

Of the seventeen critical infrastructure and key resource sectors identified by the U.S. government, the transportation sector has one of the highest degrees of interdependency, enabling or facilitating access to components in all the other sectors [1]. The major transportation modes in the United States comprise approximately four million miles of highways, 100,000 miles of rail, 600,000 bridges, 300 tunnels, countless sea ports, two million miles of pipeline, 500,000 train stations and more than 500 public-use airports [2]. Each of these individual transportation components has properties that can be modeled spatially (e.g., location and elevation) and utilized to develop mathematical models that are strongly tied to real-world networks and scenarios.

Mathematical modeling and optimization have been used extensively to solve transportation-based problems. A variety of complex, real-world problems can be modeled and solved by representing a transportation system as a graph composed

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of nodes (i.e., intersections) and arcs (i.e., road segments). Transportation networks have been used as the basis for the p-median, p-center and p-covering problems, which determine the optimal location of p new facilities given a set of existing facilities and some measure of individual facility service or demand requirements [3]. Such problems have been used in supply chain management as well as for positioning public service centers such as police stations, fire stations and hospitals [4]. Transportation networks have also been used in a variety of routing contexts from the well-known traveling salesman problem to hazardous materials routing (e.g., finding obnoxious paths and modeling transportation risks) [5,6].

This paper extends the shortest path network interdiction problem (SPNIP), a derivative of network interdiction [7,8], in which the competing objectives of an attacker and a defender are modeled as a discrete bi-level mixed integer program [9,10]. The SPNIP extension improves the ability to incorporate dynamic/mobile sensors through extended data management, pre-processing, analysis and visualization techniques using geographic information systems (GISs). The proposed method exhibits more flexibility with regard to modeling a complex physical environment, less correlation between network/region size and computational complexity, and more robustness for application to different networks/regions. Referring to the SPNIP formulation of Yates and Casas [11] as the basis for the work, we note that many SPNIP models consider the allocation of resources as a static decision whereas this paper proposes a method to expand these models to cases of dynamic (i.e., mobile) sensors. Additionally, the modeling of static sensor resources is expanded to be a function of arc length under heterogeneous sensor coverage instead of the traditional binary approach (i.e., an arc is either "covered" or "not covered"). A GIS is used to derive these spatial coverage relationships and manage them within a relational database.

The remainder of this paper is organized as follows. Section 2 reviews the literature and defines the contribution of the proposed interdiction model. Section 3 reviews the notation and terminology used in this paper and details the solution approach for deriving optimal resource allocation strategies. Section 4 introduces and discusses the proposed SPNIP model. Section 5 discusses the computational results obtained in a case study involving a California highway subnetwork. Section 6 presents the conclusions.

2. Related work

Traditional optimization problems such as network interdiction and vehicle routing have been adapted for use in the domain of homeland security. Formulations derived from minimum cost flow [12–14], discrete fractional programming [15], vehicle routing [16] and network design models [17,18] have examined such problems. List and colleagues [19] discuss modeling approaches and concerns pertaining to the transportation of hazardous materials. Many current applications in homeland security, including the network interdiction problem, were first presented and addressed in this context.

Network interdiction is typically modeled as a two-player game, where an attacker seeks to destroy or disable a set of network arcs to minimize the maximum flow across the network and a defender incurs an expense to protect or fortify network arcs (a budget limits the defender's protection capabilities such that only a limited number of network arcs may be protected). The problem has been applied to energy systems and the flow of electricity, to cyber infrastructure and the flow of information, and to transportation systems and the flow of traffic. Lim and Smith [20] describe this multicommodity network interdiction flow problem for a discrete case (arcs are either disabled or unaffected) and a continuous case (partial arc destruction is allowed). In their work, the attacker and defender have the same assumptions with regard to arc capacities, current flows and the unit price or impact of arc destruction or disablement. This information assumption, known as the assumption of perfect information, is relaxed in [21]. Asymmetric information assumes that the attacker and defender have different levels of information regarding the network, such as different arc valuations or parameters (e.g., arc capacities and arc flows). Another form of the network interdiction problem models an attacker attempting to maximize the minimum shortest path from an origin to destination. Israeli and Wood [9] focus explicitly on this problem and develop solution procedures that exploit the properties of the mathematical formulation.

Regardless of the application domain, researchers have been slow to address spatial issues and the incorporation of spatial decision-making within mathematical models. Wright and colleagues [22] describe many alternative optimization models in homeland security, but do not consider spatial implications or include GIS usage. Also in the homeland security domain, Wein and Atkinson [23] have developed a detection and interception model for the smuggling of nuclear materials. The model excels in its theoretical methodology, but its applications are restricted to small scenarios and the interception modeling results are based on geometric principles and regional discretization and, thus, have practical limitations when scaled to a realistically-sized network/region. Brown and co-workers [10] have developed bi-level mixed integer programs for border patrol detection, but they limit spatial analysis to visualization via a GIS. Mitisziw and Murray [24] adapt a binary integer survivability model [25] for disaster vulnerability assessment, but again relegate spatial concerns to the visualization of solutions in a GIS. Murray and colleagues [26,27] consider flow interdiction optimization models with applications in telecommunications networks and a reliability/vulnerability model examining network resiliency in extreme events. In each case, a GIS is again the spatial tool of choice and is used primarily for visualization, although both works also reference the use of a GIS for data collection and management. Horner and Downs [28] have developed a multi-objective approach, similar to standard facility location-allocation formulations, to identify locations for intra-urban relief distribution centers.

This paper proposes a methodology that strongly incorporates GIS and spatial data to feed into and integrate with optimization. Once validated, the approach may be used to examine and develop solution techniques (i.e., heuristics and algorithms) that use spatial parameters and properties as a