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Discrete Optimization

The maximin HAZMAT routing problem

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ABSTRACT

The hazardous material routing problem from an origin to a destination in an urban area is addressed. We maximise the distance between the route and its closest vulnerable centre, weighted by the centre's population. A vulnerable centre is a school, hospital, senior citizens' residence or the like, concentrating a high population or one that is particularly vulnerable or difficult to evacuate in a short time. The potential consequences on the most exposed centre are thus minimized. Though previously studied in a continuous space, the problem is formulated here over a transport (road) network. We present an exact model for the problem, in which we manage to significantly reduce the required variables, as well as an optimal polynomial time heuristic. The integer programming formulation and the heuristic are tested in a real-world case study set in the transport network in the city of Santiago, Chile.

1. Introduction

The hazardous material (HAZMAT) routing problem has been extensively studied in recent decades. For the most part it has been treated as a least cost routing problem between an origin and a destination, in which cost is a combination of transport costs and a risk function.

Although there is no consensus on the best way to model risk, it is generally agreed that any formulation will include two elements: the probability of an accidental HAZMAT release, and its associated consequences. Very few of the risk measures take into account the distance between a population centre and the HAZMAT route except in order to define distance thresholds within which the consequence or risk is total and beyond which it is non-existent. In reality, however, the closer a HAZMAT vehicle passes to a population centre within such a threshold, the greater is the centre's exposure to hazard (where hazard is understood as the potential for producing an undesired consequence without regard to the probability of its occurrence). This observation also fits with public perceptions, strongly suggesting that the distance between routes and populated centres warrants greater attention in HAZMAT route modelling, since it is a good proxy for hazard.

Our contribution is oriented to propose an approach oriented to the protection of vulnerable centres, together with a new model and an optimal heuristic for HAZMAT transportation in urban areas. The approach assumes that population in residential or low-rise commercial areas is easier to evacuate, but there are vulnerable centres concentrating high populations of children, senior citizens or ill people, for which is difficult to evacuate or can slowly do so. These vulnerable centres are represented as points on a plane. We incorporate in a new model, the distance between a vulnerable centre and a HAZMAT transport route. A maximin objective is used here that, to the best of our knowledge, has not previously been used in the HAZMAT or routing literature in a network context. This objective maximises the minimum Euclidean distance between the route and the nearest vulnerable centre, the distance being weighted by the centre's population. We remark that any other distance and hazard measure could be trivially used, as long as it is non-increasing with distance. Since we explicitly assume that hazard is an attribute of each vulnerable centre and depends on the centre's distance from a HAZMAT route, by using this maximin approach we minimize the hazard facing the centre closest to the route (the most exposed centre). By using this approach, we obviate the need to set risk or risk difference thresholds, or to compute probabilities. Moreover, the formulation we develop designs a route instead of choosing one from a set.

Maximal values of risk or hazard have seldom being minimized in the HAZMAT literature. In general, the average or total risk or hazard has been the objective to be minimized. Exceptions are some works that locate either straight or broken lines in a plane. However, HAZMAT transport in practice takes place over a network. Modelling the routing problem in a network context, with an integer programming formulation, requires the application of

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constraints that will relate each population centre to its closest link in the route (*i.e.*, the link imposing the greatest hazard). This type of constraints is used in discrete location problems, e.g., assigning customers to the closest plant of a multi-plant firm.

The new exact model we formulate here (our first solution method) potentially requires a large number of closest assignment constraints. Normally, this would also mean a large number of decision variables, significantly complicating the solution of the problem. Since the route is not known *a priori*, a variable associating each vulnerable centre with each network link has to be added, implying a total of $O(mq)$ variables where m is the number of network links and q the number of vulnerable centres. In our exact model, however, each vulnerable centre needs only a subset of these variables identified by the sections of route within the centre's danger area. The result is a major reduction in the required number of variables and constraints. Although the problem can be solved using an optimal heuristic also presented here, we offer both procedures, as the variable reducing technique could be applied to harder problems.

Our second approach corresponds to an optimal heuristic, which solves the problem in polynomial time and can be used easily for large real instances.

The remainder of this article is organised into four sections. In Section 2, we offer a Literature review. Section 3 formulates the maximin problem for hazardous materials routing as an exact formulation and includes an optimal heuristic; Section 4 describes a practical application of the proposed methodology and analyses the results; and finally, Section 5 presents our conclusions and some possibilities for future research.

2. Literature review

2.1. Risk and distance dependent danger

Erkut, Tjandra, and Verter (2007) have identified nine different risk estimators: the exposed population (ReVelle, Cohon, & Shobrys, 1991); the probability of an accident (Abkowitz, Lepofsky, & Cheng, 1992; Saccomanno & Chan, 1985; Marianov & ReVelle, 1998); the expected consequence, defined as the product of the probability of an accident and its associated consequences (Alp, 1995; Batta & Chiu, 1988; Pijawka, Foote, & Soesilo, 1985; Erkut & Verter, 1995); the expected consequence given that an accident has occurred along the route (Sivakumar, Batta, & Karwan, 1993, 1995; Sherali, Brizendine, Glickman, & Subramanian, 1997); risk aversion, the perceived risk along a link being measured as pC^q, where p is the probability of an accident on the link, C is the consequence of an accident and q is a risk preference parameter (Abkowitz et al., 1992); a demand satisfaction model proposed by Erkut and Ingolfsson (2005) in which an accident terminates a trip, necessitating a new shipment to fulfil demand; the maximum exposed population (Erkut & Ingolfsson, 2000); simultaneous consideration of the expected value and variance of the number of people affected by an accident (Erkut & Ingolfsson, 2000); and expected disutility, using a disutility function of the form $u(X) = \exp(\alpha X)$ where X is the affected population and $\alpha > 0$ a constant measuring catastrophe aversion (Erkut & Ingolfsson, 2000).

In addition to these nine estimators, Jin and Batta (1997) propose six ways of modelling risk based on expected consequence in terms of the number of HAZMAT shipments or trips S to be made and the threshold number of accidents Q. In these formulations, shipments cease once a number Q of accidents have occurred or when S trips have been made, whichever comes first. The shipments are considered as a sequence of independent Bernoulli trials and a trip terminates if either an accident occurs or the destination is reached.

Some authors incorporate equity into the spatial distribution of risk in HAZMAT routing. For example, Zografos and Davis (1989) include the concept indirectly by placing flow capacity constraints on the various links in the transport network. Marianov and ReVelle (1998) propose stipulating an upper bound on the total risk associated with each link. Gopalan, Batta, and Karwan (1990a) consider a route defined by an origin–destination pair to be equitable if the difference between the risk levels imposed on any pair of zones in the neighbourhood of the route stays below a preset threshold. They calculate the risk associated with a link in the route as the sum of the risks imposed on the various zones in the link's neighbourhood, an approach that could double-count part of the population. The same authors extend their model in Gopalan, Kolluri, Batta, and Karwan (1990b) to identify a set of routes for making T trips between a single origin–destination pair. They minimize the total risk over the T trips while maintaining the difference in total risk between every zone pair under a certain equity threshold, the latter given for any pair by the differences in risk summed over the T trips. Lindner-Dutton, Batta, and Karwan (1991) take this model further, focusing on the search for an equitable sequence for the T trips. They minimize the sum of the maximum differences in risk between any zone pair accumulated over t trips ($t = 1, \ldots, T$). Other approaches to the equitable risk distribution for a set of trips between a given origin–destination pair may be found in Dell'Olmo et al. (2005) and Caramia, Giordani, and Iovanella (2010).

All of the above-mentioned works use subjective risk thresholds without defining any standard. Moreover, they all consider risk as an attribute of the route links rather than the population centres along it. This approach, if not used carefully, could lead to under- or overestimation of both risk itself and the differences in risk between population centres.

Risk measures do not incorporate distance. However, hazard, defined by Rasmussen (1981) as the potential for producing an undesired consequence without regard to the probability of its occurrence does depend on distance. The phenomenon is acknowledged by Saccomanno and Shortreed (1993), Jonkman, van Gelder, and Vrijling (2003), Fernández, Fernández, and Pelegrín (2000) and Karkazis and Boffey (1995), who note that distance should be a factor to incorporate in models dealing with HAZMAT transportation.

Three studies which do incorporate distance into their formulations are Erkut and Verter (1995), Carotenuto, Giordani, and Ricciardelli (2007) and List and Mirchandani (1991). In the first one, two models are proposed. The first model assumes population concentrated at points on a plane, while the second treats population centres as two-dimensional objects. Both models use probabilities (of an accident, of an incident given an accident, and probability of a material release) that are difficult to estimate. In the paper, the models are used to choose among several routes. In Carotenuto et al. (2007), assuming the population is located on the transport network links (populated links), the authors calculate, for each unit-length segment x of a link, the risk imposed by its use for HAZMAT transport on each populated segment y in the network. The calculation is made only within a threshold distance measured from the centre of segment x. For each populated segment y within that distance, the authors multiply the population along that segment by a function that decreases exponentially with the distance between the two segments and the probability of an incident on segment x. The sum of the risks imposed by the use of each segment x of a link gives the total risk associated with that link, and by the same token, the total risk imposed by a route is the sum of the risks imposed by each of its constituent links. Heuristic procedures are applied to generate a set of alternative routes between an origin–destination pair and the total risk is then minimized, with a preset upper limit on the total risk over the populated links. Note, however, that this methodology could generate