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The Gateway Location Problem: Assessing the impact of candidate site selection policies

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ABSTRACT

The Gateway Location Problem (GLP) is a new combinatorial optimization problem arising in the framework of rule-based risk mitigation policies for hazmat vehicle routing. GLP consists of locating a fixed number of check points (so called *gateways*) selected out of a set of candidate sites and routing each vehicle through one assigned gateway in such a way that the sum of the risks of vehicle itineraries is minimized.

This paper addresses a GLP preparatory step, that is, how to select candidate sites, and it investigates the impact of different information guided policies for determining such a set. Indeed, previous results pointed out that this stage of the process can impact not only the efficacy of the method, i.e., the risk level associated with the solution itineraries, but also the efficiency of the method with regard to the number of sites to be considered. All policies consist of selecting a ground set and sampling it according to a probability distribution law. A few criteria are proposed for generating ground sets as well as a few probability distribution laws. A deterministic variant based on a cardinality constrained covering model is also proposed for generating candidate site sets. All policies have been tested and compared against plain random generation through extensive testing on a set of realistic instances characterized by three different risk measures. Results confirm that a careful choice of the candidate site set is a critical step of the whole GLP based risk reduction process.

A complexity proof of NP-hardness of GLP is also provided.

1. Introduction

Hazardous materials pervade our daily lives in many ways. The gasoline fueling our cars, radioactive and contaminated hospital waste, special drugs sold by pharmacists, the chemicals utilized in car body repair shops, are all examples of substances which pose little threat if properly used but can turn quite harmful to people and the environment if accidentally spilled. The most likely situation in which accidental release of hazardous materials (hazmat) can occur is during transportation. While the probability of an accident is generally very low, consequences can be extremely deleterious. Such a concern, fueled by a few fatal accidents that have occurred in the last few years, has motivated research on risk mitigation in hazardous material transportation. Much has been done on the prevention side, such as enforcing strong safety rules on material handling and packaging, as well as on the vehicles used for transportation. In the case of road transport, a critical

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step in the decision making process concerns vehicle routing, i.e., the selection of itineraries to be followed by hazmat vehicles on their trips from origin to destination. In the *unregulated scenario*, without prescribed directions, drivers are expected to select their minimum cost route among all possible origin–destination itineraries. The progressive urbanization of city outskirts has resulted, in many cases, in an incongruous mix of residential and industrial land uses. As a result, hazmat vehicle routes may cross residential areas (unless explicitly prohibited) when origins and destinations are located within mixed industrial–residential areas. Therefore, when entirely left to drivers, route selection may yield extremely risky itineraries, which generally should be avoided. At the same time, there may be alternative itineraries which are still economically acceptable to drivers but quite different with respect to risk. Drivers should be supported in this critical decision making step in order to make risk aware choices.

For some specific shipments, an ad hoc itinerary can be entirely planned and prescribed by the authority in charge of the regulation. In this case we speak of the *over regulated scenario*. However, this cannot be assumed to be common practice, since the burden of full control on route enforcement for each shipment would not be affordable. A more viable alternative to the over regulated scenario is to indirectly encouraging safer itineraries, rather than enforcing them, by exploiting the supposedly rational behavior of drivers. In such a *rule-based scenario*, the authority promulgates a set of common rules, easy to check, with which drivers must comply. Such rules, in order to be effective, must be stated by taking driver reactions into account. For this reason the problems arising in the rule-based scenario usually give rise to bilevel optimization problems, which properly model the hierarchical relationship between the decision makers. Examples are the closure of some links of the network to hazmat vehicle transit or specific pricing policies on the network links. The most significant contributions to hazmat routing are briefly discussed in Section 2.

The Gateway Location Problem (GLP) arises precisely in the framework of rule-based routing. It consists of locating a fixed number of check points (so called gateways) selected out of a set of candidate sites and assigning one such gateway to each vehicle as a compulsory crossing point along its itinerary in such a way that the sum of the risk of the minimum cost route of each vehicle from its origin to its destination via the assigned gateway is minimized.

GLP was first introduced in [2] where its efficacy as a risk mitigation tool was tested on a set of realistic instances. In [2] it was assumed that the set of candidate sites among which gateway locations are selected is randomly sampled out of the whole set of network nodes, according to a uniform probability distribution. While, for a given number of open gateways, the level of risk mitigation obviously does not decrease by enlarging the candidate site set up to considering all nodes in the network, in [2] it was also shown that a good level can be reached by way of an intelligent selection of a limited number of nodes. Such a procedure becomes a compulsory step when tackling instances related to large size urban areas, whose networks easily reach into the thousands of nodes. In such a case, the size of the candidate site set may become a distinct problem. This paper aims at providing adequate policies for this step. Section 4 is devoted to their introduction. In particular, we experimentally investigate the influence of different criteria for the selection of the ground set out of which the candidate sites will be generated according to a probability distribution; moreover, we analyze the impact of different probability distribution laws used for sampling. Indeed, previous results pointed out that this stage of the process, i.e., candidate site generation, can impact not only on the efficacy of the method, i.e., the risk level associated with the solution itineraries, but also on the efficiency of the method. In fact, [2] provides experimental evidence that a wise choice of candidate sites may reduce the number of candidate sites to be considered in order to achieve target risk mitigation thresholds. Section 5 is devoted to the experimental comparison. The proposed policies are compared against plain uniform random generation through a wide experimental campaign which is based on the results of the associated GLP run on a set of realistic instances and considers both quality and robustness of the results. In order to make the analysis less data dependent, the test bed encompasses instances characterized by three different risk functions. Conclusions are finally drawn in Section 6.

The GLP is not only the core of a new method for risk mitigation, but it also introduces a new problem in combinatorial optimization. In Section 3, after recalling the problem structure, we provide the first complexity proof of NP-hardness of GLP and highlight its relations with well known NP-hard problems.

2. Literature review

Two main research lines can be identified in the literature on risk mitigation policies to regulate the itineraries of the hazmat shipments: (i) enforcing specific itineraries to vehicles in the framework of an over regulated scenario; (ii) prescribing a set of rules that vehicle itineraries have to respect in a rule-based scenario.

Regarding the first research line, several criteria can be used to evaluate the quality of a given itinerary. Indeed, risk assessment studies propose several alternative risk measures, such as societal risk, population exposure, and incident probability. At the same time, however, carriers aim at cost reduction, usually achieved by minimizing travel time or travel distance. All these criteria are potentially conflicting and naturally lead to multi-objective flow problems as studied in [12,19]. Solution methods for hazmat routing are usually distinguished between local and global ones, as documented in [20].

Local routing is concerned with selecting a set of routes between a given origin–destination pair for the repeated shipment of a single commodity. The main issue concerns the equitable spread of risk among the population [11]. In this case, not only the total risk should be minimized, but the risk should also be distributed in the most uniform way over the whole transport region. This problem leads to the search for spatially dissimilar paths which can be addressed by various modeling approaches, e.g., by means of the Iterative Penalty Method [18], by means of the Gateway Shortest Path [15], by