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Applying genetic algorithm to a new bi-objective stochastic model for transportation, location, and allocation of hazardous materials

Ehsan Ardjmand[a], William A. Young II[b], Gary R. Weckman[a,*], Omid Sanei Bajgiran[c], Bizhan Aminipour[a], Namkyu Park[a]

[a] Department of Industrial and Systems Engineering, Ohio University, Athens, OH 45701, USA
[b] Management Department, College of Business, Ohio University, Athens, OH 45701, USA
[c] Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada

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ABSTRACT

In 2013, approximately 15,600 HAZMAT accidents with 158 injuries and fatalities have been reported in the USA ("Transportation Statistics Bureau"). Managing hazardous material (HAZMAT) transportation and locating the disposal sites for these materials properly can significantly reduce the risk of accidents and its environmental and social aspects. In this research, a new stochastic model for transportation, location, and allocation of hazardous materials is proposed. The cost of transportation is considered to be of a stochastic nature. The objective function minimizes the total cost and risk of locating facilities and transportation of HAZMATs. The decisions which have to be made are: (1) where to open the facilities and disposal sites; (2) to which facilities every customer should be assigned; (3) to which disposal site each facility should be assigned; and (4) which routes a facility should choose to reach the customers and disposal sites. A novel genetic algorithm (GA) is applied to the model. The results show the efficiency of the proposed GA in terms of finding high quality solutions in a short time.

1. Introduction

Due to undesirable effects of hazardous materials (HAZMAT) on the environment and the emerging environmental issues involving locating facilities and the transportation of HAZMAT has attracted a lot of researchers to hazardous material management (HMM) in the past decades (Moungla & Jost, 2010; Triantafyllou & Cherrett, 2010). Many industries produce materials which can have negative effects on the environment either directly or indirectly, and these need to be treated properly (Samanlioglu, 2012). There are four main topics in HMM (Moungla & Jost, 2010; Nema & Gupta, 1999) namely, routing/scheduling (List, Mirchandani, Turnquist, & Zografos, 1991), risk analysis (Erkut & Ingolfsson, 2005), sitting or location (Murray & Church, 1995), and treatment of residue or waste (Nema & Gupta, 1999). Many mathematical models have been developed to address these issues. Most of these models address the HMM by taking into account only one aspect of it – i.e. routing/scheduling, risk analysis, location and treatment (Alçada-Almeida, Coutinho-Rodrigues, & Current, 2009; Carotenuto, Giordani, & Ricciardelli, 2007; Coutinho-Rodrigues, Tralhão, & Almeida, 2012; Erkut & Ingolfsson, 2000, 2005; Karkazis & Boffey, 1995; Koo, Shin, & Yoo, 1991; Li, Leung, Huang, & Lin, 2012, 2013; Ma et al., 2012; Meng, Lee, & Cheu, 2005; Mote, Murthy, & Olson, 1991; Nema & Gupta, 1999; Patel & Horowitz, 1994; Pradhananga, Taniguchi, & Yamada, 2010; Tang, Boyer, Pedram, Yusuff, & Zulkifli, 2013; Yuejie, Jing, & Kai, 2010).

HMM has also been investigated under stochastic conditions. Wijeratne, Turnquist, and Mirchandani (1993) proposed a method for obtaining various non-dominated solutions – i.e. routes – in a network in which each path is described by a set of stochastic values. Karkazis and Boffey (1995) modeled the routing problem of HAZMATs, showing that the risk of transportation can vary due to the distribution of a population. Miller-Hooks and Mahmassani (1998) formulated the HAZMAT routing problem in a time-varying network, where travel time and risk were considered to be dynamic over time. Chang, Nozick, and Turnquist (2005) analyzed the same problem, where the properties of the routes were probabilistic and its distribution function could have different variations at different times. Meng et al. (2005) modeled the combination of a HAZMAT routing and scheduling problem in a network with multiple time-varying properties. Dadkar, Jones, and Nozick (2008) developed a *k*-shortest path algorithm to identify the various routes in a highway which have the same overall performance regarding

* Corresponding author. Tel.: +1 740 593 1548.
E-mail addresses: ardjmand@ohio.edu (E. Ardjmand), youngw1@ohio.edu (W.A. Young II), weckmang@ohio.edu (G.R. Weckman), o_sane@encs.concordia.ca (O.S. Bajgiran), bizz.pt@gmail.com (B. Aminipour), parkn@ohio.edu (N. Park).

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HAZMAT transportation. Jia, Zhang, Lou, and Cao (2011) took advantage of a fuzzy-stochastic constraint programming approach to model a scenario where a HAZMAT cargo may be threatened by a terrorist attack.

One interesting problem in HMM is the issue of simultaneous locations of undesirable facilities and the routing of HAZMATs. ReVelle, Cohon, and Shobrys (1991) conducted some of the first research in this domain. Their model tended to minimize the cost and risk of establishing storage facilities and transportation of fuel rods from a nuclear plant. Jacobs et al. (1994) formulated a linear programming model for simultaneous routing-location of hazardous material, with perceived cost and risk as objective functions. Helander et al. (1997) formulated the same problem, while considering the risk as the expected number of accidents. Giannikos used a goal programming method, in which the objective function was composed of total risk and cost, as well as the distribution of risk and futility due to treatment centers' activities in residential areas. Cappanera, Gallo, and Maffioli (2003) used Lagrangean relaxation and branch-and-bound approaches for solving the HAZMAT routing-location problem. Alumur et al. (2007) modeled the same problem, while considering the technology which HAZMATs should be treated with as a decision variable. Their research was further elaborated later by Dai et al. (Dai, Yu, & Zhu, 2011) and Samanlioglu (Samanlioglu, 2013).

In this paper, a new bi-objective model for the routing and location of HAZMATs in a network is proposed where the cost of transportation is considered to be stochastic. This assumption is important, due to the variation of transportation costs as a result of changing situations in transportation networks. In reality, decisions about the locations of facilities have to be made earlier. Location decisions have to be robust enough to impose the least amount of cost on the system in terms of transportation, which are subject to higher variation. This variation can be caused by many factors, such as road conditions, seasonal changes, fuel price, etc.

One very important aspect of the proposed model is risk minimization. Choosing different risk criteria can provide us with different solutions. Although risk assessment is not the focus of this research, it is essential to define the risk element and how it is incorporated in the model. The risk structure considered in this research is environmental, and is similar to the risk introduced by Zhao and Verter (2014). They define the environmental risk as the area (m^3) around the transportation route, facilities, and disposal sites that might possibly impacted somehow by HAZMAT pollution. For a route, this area depends upon the route length and impact radius, which itself depends on the HAZMAT type. The impact radius for a facility or disposal site depends on the concentration (mg/m^3) of HAZMAT, which itself is a function of release rate (m^3/s), average downwind speed, distance from the source, height of the source, and dispersion potential of the HAZMAT (Zhao & Verter, 2014).

In this research, in order to integrate the risk and cost factors into one objective function, these two factors will be weighted linearly. This method is widely used in the relevant literature (Alumur & Kara, 2007; Zhao & Zhao, 2010). Hence, the proposed bi-objective model will transform into a single objective problem. In real-world cases, the weights of cost and risk are determined by decision makers, and by changing them it is possible to evaluate various scenarios.

The model is single-product and single-period, where each customer and facility is assumed to be connected to only one facility and disposal site, respectively. The decisions which have to be made to optimize the objective function are: (1) where to open the facilities which produce HAZMAT; (2) where to open disposal sites; (3) to which facilities every customer should be assigned; (4) to which disposal site each facility should be assigned to; (5) which route a facility should choose to reach the customers; and 6) which route a facility should choose to reach a disposal site.

Solving the problem formulated in this research is computationally very expensive, and can require a lot of processing power to solve it precisely for real-life cases. The main reason for this is that in real scenarios, the dimension of the problem tends to be huge, and applying an exact solving method to it may not be possible. Hence, it is necessary to use a heuristic method that is specifically designed to solve the proposed problem efficiently. A significant amount of research has been conducted to address this issue in HMM literature. Kim, Kim, and Sahoo (2006) presented a clustering-based waste collection algorithm, and showed its efficiency by applying it to a series of large-scale real-world scenarios. Their method is an extended version of the insertion algorithm, where the compactness and workload balancing of its solutions and computational time are improved. Verma et al. (Verma, Verter, & Zufferey, 2013) proposed a tabu search algorithm for planning the rail–truck intermodal transportation of HAZMATs. They applied their method to a real-world problem with 37 locations with hypothetical demand data, and found that the regular containers tend to choose the shortest paths between the origin and destination, particularly when compared to HAZMAT containers. Pradhananga et al. (Pradhananga et al., 2010) used an ant colony system (ACS) for multi-objective optimization of hazardous material (HAZMAT) transportation. They integrated their method with a labeling algorithm for finding non-dominated paths to improve its performance.

Since the problem of the presented paper is unique in literature and computationally expensive for large instances, it is necessary to have a heuristic designed for it. In this research, a genetic algorithm (GA) with a two-dimensional chromosome structure for solving the proposed model is introduced and examined. The suggested GA, as will be illustrated and supported by numerical experiments, is very efficient in solving large-scale problems, and hence can be applied to real-world scenarios.

The contribution of this paper is threefold. First, a new stochastic model for location, allocation, and routing of hazardous materials is proposed, in which the transportation costs have a probabilistic nature. Note that in almost all real-world problems, transportation cost stochasticity is present, and it is very important to address this issue in these models. Second, a novel GA that can handle uncertain transportation costs is introduced. Third, the efficiency of the proposed GA is evaluated by solving several problems of various sizes. Note that since the transportation costs are stochastic, there are two types of decision variables in this problem. Some decision variables need to be determined before the transportation cost is realized (such as location of disposal sites), and some need to be determined after the real transportation cost is observed (such as the transportation routes). Hence, the location of facilities and disposal sites should be determined in a way that, under all realizations of the transportation cost, the overall cost and risk stay as low as possible. The proposed GA is able to achieve this goal by using a novel chromosome structure.

The remainder of this paper is organized as follows. In Section 2, the deterministic model and its stochastic counterpart in which the transportation costs are probabilistic are presented. In Section 3, the proposed GA is introduced, while in Section 4, numerical experimentations are presented. In Section 5, some possible future directions for the research are presented. Finally, in Section 6, the overall conclusion is stated.

2. Model

Consider a graph consisting of some nodes and edges which are representative of different locations and routes on a geographical map. Customers, candidate facilities and disposal sites are located on the nodes of this graph. The HAZMAT transportation, location,