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Cost and risk aggregation in multi-objective route planning for hazardous materials transportation—A neuro-fuzzy and artificial bee colony approach

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ABSTRACT

This paper proposes a new approach for cost and risk assessment in the multi-objective selection of routes for the transport of hazardous materials (hazmat) on a network of city roads. The model is based on the application of an Adaptive Neuro Fuzzy Inference System (ANFIS). The values of the cost and risk criteria are, using an adaptive neuro-fuzzy network trained with an Artificial Bee Colony (ABC) algorithm, integrated into a single CR value by means of which the worthiness of each branch in the network is expressed, and after which the selection of the route is made using Dijkstra's algorithm. The ANFIS adequately treats a number of uncertainties and ambiguities in the input data and enables the inclusion of the knowledge of experts and the preferences of the decision makers. The procedure is also applicable in cases in which the decision maker does not have high quality data available. The proposed model is tested in a real urban route planning problem, in a case study of the distribution of oil and oil derivatives in Belgrade, Serbia.

1. Introduction

When managing transport, the mitigation of its negative consequences is often highlighted, particularly those concerning safety and the environmental impact. Because of the extent of the possible harmful consequences, managing the transport of hazardous materials, particularly in city areas, is an issue requiring a great deal of attention. A number of hazardous materials (hazmat) can be found in the literature related to transportation studies. According to Xie, Lu, Wang, and Quadrifoglio (2012), the problems considered in the literature can be classified into several categories: network design studies, risk modeling studies, development of decision support systems, facility location studies, integrated location and routing studies, and vehicle routing and scheduling studies. Among them, the problem of vehicle routing is one of the most commonly tackled problems.

Route selection basically belongs to the class of shortest path problems, which are generally considered as single-objective problems, and which are encountered in the majority of the given categories of problems. In this context, the objective is usually to have the minimum total distance or travel time between two nodes (origin and destination node). In such an approach the routes are mainly generated by shortest path algorithms (modified Yen's algorithm for the k-shortest path problem in Carotenuto, Giordani, & Ricciardelli, 2007, the successive shortest path algorithm in Leonelli, Bonvicini, & Spadoni, 2000, Dijkstra's shortest path algorithm in Frank, Thill, & Batta, 2000). In the majority of cases a single-objective approach is not enough.

Given the clear interest in the transport of hazmat from the majority of stakeholders (industries, shippers, carriers, end users, government bodies, regulatory agencies, emergency response organizations, population exposed to risk, organizations that maintain the road network and others), all of whom have different, and in principle, conflicting interests, it is obvious that the problem of routing hazmat is a multi-objective one. Multiple actors are involved in solving this problem, and as a result, the solutions require a lot of compromises. The essence of the compromises can be seen in a set of criteria for the selection of routes that are present in the decision making model. In addition, a big problem for decision makers is the availability and reliability of the data needed to make decisions, as well as models of risk evaluation for the transport of hazmat.

The problems of vehicle routing are often solved as bi-objective problems, usually by integer programming and by heuristic

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approaches (Androutsopoulos & Zografos, 2010; Bronfman, Marianov, Paredes-Belmar, & Lüer-Villagra, 2015; Duque, Lozano, & Medaglia, 2015; Fan, Chiang, & Russell, 2015; Kuhn, Raith, Schmidt, & Schöbel, 2016; Siddiqui & Verma, 2015; Xie & Waller, 2012). As an extension of bi-objective models, there are also examples of the multi-criteria approach to route planning (Bowen & Ciyun, 2015; Paixão & Santos, 2013; Pulido, Mandow, & de la Cruz, 2014). According to Samanlioglu (2013) and Xie et al. (2012), the most common multi-objective approach to the problem is based on the principles of the weighted sum method. By means of this method, all criterion functions (most often those related to cost and risk) are multiplied by the appropriate weight coefficient and summed in an aggregated objective function. In this way, the multi-objective problem of route selection is reduced to a single-objective, which can be solved by some of the shortest path algorithms.

Therefore, Lue and Colorni (2015) proposed the risk assessment model, by means of which they determined the "total cost attribute" for each link of the urban network, after which they selected routes for hazmat transport using the Dijkstra algorithm. They considered the objectives to be: travel cost, exposure of the population, environmental risk (risk to territorial infrastructure, natural elements and critical areas) and security concerns. They also emphasized that the weight elicitation problem is present in the model.

Even if determining the weight coefficients of the attributes does not present a problem to the decision maker, there is also the question of selecting the method of normalizing the estimated value of the attributes assigned to each link. Gal, Stewart, and Hanne (1999) proposed multi-criteria decision analysis as an option for overcoming the problem of determining the weight coefficients. Multi-criteria analysis is used as a tool to achieve the best possible trade-offs among different objectives (Li & Leung, 2011). At the same time it should be kept in mind that the optimality of multi-objective solutions in the domain of hazmat routing involves Pareto-optimality (more about the Pareto concept can be seen in Das, Mazumder, & Gupta, 2012). Apart from this, a known drawback of the weighted sum approach is its unreliability in detecting non-supported Pareto–optimal solutions.

Li and Leung (2011) also considered the problem of routing in the transportation of hazmat in an urban network as a multi-objective optimization problem. They proposed the compromise programming approach for the modification of Dijkstra's algorithm, while for determining the weight coefficients of the attributes they used the Analytic Hierarchy Process, believing that in this way they were minimizing human subjectivity in decision making.

In previous studies on routing hazmat transportation, it is mainly models of a deterministic character that have been proposed, the application of which requires exact data. However, high quality data about the probability of accidents, the population affected by accidents, the population distribution (on-road and off-road population), population fluctuation, traffic flows etc. are not always available. Here it should be kept in mind that no states, regions or cities have equally developed information systems, and consequently the amount and quality of data required varies from region (network) to region (network). Given the specificity of such data, they are usually not comparable between different areas. In addition, these data are time-dependent (on a daily or seasonal basis), and uncertainty also exists in real situations. A way to deal with such uncertainty is to use stochastic or fuzzy variables based on the type of uncertainty in the problem (Hossein, Zarandi, Hemmati, Davari, & Turksen, 2014). If only a little information is available, a stochastic approach is not reliable and fuzziness performs better results (Meiyi, Xiang, & Lean, 2015a).

Thus, in Meiyi, Lean, and Xiang (2015b), a chance-constrained programming model was presented, within the framework of credibility theory, for solving the hazmat location-routing problem. Assuming that the transportation costs and the number of affected people are the fuzzy variables, they designed a fuzzy simulation-based genetic algorithm (GA) to solve the problem. In Zahedian-Tejenaki and Tavakkoli-Moghaddam (2015), a bi-objective model was developed for hazmat routing on an intermodal (rail-truck) transit network, in which, again, the cost of transiting and exposure of the population were considered as fuzzy values. In 2006, Boulmakoul proposed a solution for the k-best fuzzy shortest paths problem in the context of hazmat routing, considering the environmental, infrastructure and economic components of risk as fuzzy values.

In addition to fuzzy logic, the use of neural networks is a convenient and flexible approach to the treatment of uncertainty, imprecision and data shortfalls in hazmat transportation problems. Their greatest advantage is that they make it possible to appreciate expert opinion (implemented through a database of rules), and they are also able to learn independently and adapt based on previous experience. As with the use of fuzzy logic, the use of neural networks in hazmat routing problems is rare. To the best of our knowledge, there are only a few studies that solve the hazmat routing by means of neural networks.

In Ma, Wu, and Lu (2008), a back propagation neural network combined with a particle swarm optimization algorithm served as the base for developing a model of route evaluation in the context of factors affecting hazmat transportation safety and transportation time. A route evaluation method based on a fuzzy neural network was developed by Sun and Zha (2011), introducing the optimization index of hazmat transportation routes. Ma et al. (2013) proposed an intelligent algorithm which integrates fuzzy simulation, neural networks, stochastic simulation and genetic algorithms in order to solve the hazmat transportation routing problem.

The specifics of hazmat routing problems are the specific criteria which need to be minimized or maximized. The criteria most commonly used when solving the hazmat routing problem over the last 10 years are presented in Table 1.

Table 1 shows that many hazmat routing studies have been focused primarily on balancing the cost and risk factors. Travel time, distance and total cost estimations are the most common representatives of the carrier's interests. Total travel time and route length are often used because numerous transport costs are proportional to the time spent on the route and the length of the route. The risk depends primarily on the type and amount of hazmat transported, then on the frequency of the transport, as well as on the characteristics of the road and traffic etc. Since the calculation of risk is more complex than the estimation of the transport costs, specific models of risk evaluation are integrated into routing models.

Thus, when Kuhn et al. (2016) tested the algorithm for solving the bi-objective shortest path problem on selecting a route for a single hazmat shipment, they considered travel time to represent the cost criteria, while they calculated risk on the route as the product of the probability of an incident and the impact area of an incident on the route. Zhao and Verter (2015) proposed a weighted goal programming approach for the oil location-routing problem they used, in which they observed cost and risk as the objectives. They observed cost as a function of the fixed expenses involved with using vehicles and the costs connected with the length of the branch/route, and they observed risk as a function of the impacted area and quantity of hazmat transported. In a similar way, Funda (2013) calculated risk as the product of the exposure of the population and the amount of hazmat. Xin, Qingge, Wang, and Zhu (2015) observed risk on the network as the interval value, and with that secured the validity of the solution in cases where there is a change in the level of risk for individual branches, since the selection of the route, according to the heuristic approach they proposed, works on the principle of avoiding branches that are potentially high risk.