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Discrete Optimization

Metaheuristics for the risk-constrained cash-in-transit vehicle routing problem

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ABSTRACT

This paper proposes a variant of the well-known capacitated vehicle routing problem that models the routing of vehicles in the cash-in-transit industry by introducing a risk constraint. In the *Risk-constrained Cash-in-Transit Vehicle Routing Problem* (RCTVRP), the risk of being robbed, which is assumed to be proportional both to the amount of cash being carried and the time or the distance covered by the vehicle carrying the cash, is limited by a risk threshold.

A library containing two sets of instances for the RCTVRP, some with known optimal solution, is generated. A mathematical formulation is developed and small instances of the problem are solved by using IBM CPLEX.

Four constructive heuristics as well as a local search block composed of six local search operators are developed and combined using two different metaheuristic structures: a multistart heuristic and a perturb-and-improve structure. In a statistical experiment, the best parameter settings for each component are determined, and the resulting heuristic configurations are compared in their best possible setting. The resulting metaheuristics are able to obtain solutions of excellent quality in very limited computing times.

1. Introduction

Over the last decades, vehicle routing problems have drawn the interest of a large number of researchers, and several variants have been developed to model different real-life situations. An interesting field of application, which has not received much attention so far, concerns the issue of *security* during the transportation of cash or valuable goods between banks, large retailers, shopping centres, ATMs, jewellers, casinos, and other locations where large amounts of cash or valuables are present.

The cash-in-transit (CIT) industry groups transportation companies that deal with the physical transfer of banknotes, coins and items of value. In general the transfer of cash and valuables happens between customers (typically retail and/or financial organisations) and one or more cash deposits or banks. It is clear that, as a consequence of the nature of the transported goods, resisting crime is a significant challenge, and CIT companies are constantly exposed to risks such as robberies.

In order to estimate the importance of the CIT sector we note that in the United Kingdom alone, more than £500 billion are transported each year (£1.4 billion per day). Some robberies manage to attract a large share of media attention. In February 2013 in Foggia (Italy) 300 kilogram of gold was robbed. In the same month and year in Brussels (Belgium) a robbery of €50 million happened, and in March 2013 in Varese (Italy) a criminal organization carried out a robbery of €10 million. Money stolen in CIT attacks represents a major source of funding for organized crime. The latest statistics from the British Security Industry Association show that attacks against CIT couriers remain a serious and growing problem throughout the world (British Security Industry Association, 2013).

During the last decades, in an effort to reduce the incidence of robberies, CIT firms have heavily invested in better vehicles, equipment, infrastructure, and technologies (e.g., armoured vehicles, weapons on board, on-board drop safes and interlocking doors, active vehicle tracking). However, no level of security measures can completely prevent robberies from happening (Erasmus, 2012).

According to Smith and Louis (2010); Yan, Wang, and Wu (2012), one of the main reasons robberies are so prevalent is a lack of analysis of security issues in the route planning phase. The authors warn that a careful planning of the cash-in-transit activities is generally advisable to reduce the risk of being robbed. For this reason, a recent study of Yan et al. (2012) proposes a model to formulate more flexible routing and scheduling practices that incorporates a new concept of similarity for routing and scheduling solutions considering both time and space measures to reduce the risk of robbery.

Another approach suggested in the literature is to reduce the risk of being attacked by building routes that are "unpredictable" for criminals. In so-called "peripatetic" routing problems (Krarup, 1975;

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Ngueveu, Prins, & Wolfler Calvo, 2010a, 2010b), customers are visited several times within a planning horizon, but the use of the same arc twice is explicitly forbidden. In Wolfer Calvo and Cordone (2003) the "unpredictability" is ensured by introducing time windows with a minimum and maximum time lag between two consecutive visits of the same customer. In this way it is possible to generate a wide variety of solutions, as required for security reasons. A similar concept is followed by Michallet, Prins, Amodeo, Yalaoui, and Vitry (2014); Michallet, Prins, Amodeo, Yalui, and Vitry (2011) where regularity (in terms of time at which the visit of the customer happens) is avoided, by managing time windows in which each customer can be visited.

Except for some practical situations that explicitly require customer visits at regular intervals, the moments in time at which customers are visited are generally variable in the CIT sector depending on the amount of money that needs to be deposited or picked up, which is seldom regular. Therefore, CIT firms define their routing plan on a daily basis, depending on the customers that need to be visited. Routing plans in the CIT sector should both be safe and efficient, while taking into account two critical issues: minimization of the travelled cost/time, as well as limiting the exposure of the transported goods to robbery. The Risk-constrained Cash-in-Transit Vehicle Routing Problem (RCTVRP), that is developed in this paper, attempts to achieve this.

Different from the existing approaches known in the literature, we limit the total risk that any vehicle may incur during its operations to a pre-specified *risk threshold*. To this end, a risk index is defined to measure the exposure of the vehicle, while it is outside of the depot. To the best of our knowledge, this particular way to handle security in a vehicle routing context is new. Moreover, it is complementary to methods that achieve security through unpredictability, and can potentially be combined with them.

Informally, the RCTVRP is defined as follows. Given a depot, as well as a set of customers each with a given "demand", corresponding to a sum of cash that needs to be picked up, the objective of the problem is to define a set of routes, one for each vehicle. Each vehicle leaves from a depot, visits a set of customers picking up cash and returns to the same depot at the end of its route. On each arc it travels, a vehicle incurs a certain amount of risk that is proportional to the both time or distance travelled and the amount of cash carried on that arc. The total risk incurred by a vehicle is the sum of the individual risks incurred on each arc. For each vehicle route, this total risk should be at most equal to a predefined risk threshold that can be quantified by the CIT firm depending on a series of factors such as the amount of money to be transported, the characteristic of the network, and the company's attitude to risk. In a preliminary analytical stage several scenarios presenting different risk thresholds (see e.g. Section 5) could be evaluated and the most suitable risk threshold can be adopted by the CIT company to generate routes that are both efficient and safe.

The main focus of this work is the development of a decision model, together with the description of the solution approaches. The major contributions of this paper are fourfold.

(1) A new variant of the vehicle routing problem, the Risk-constrained Cash-in-Transit Vehicle Routing Problem (RCTVRP) is introduced. The main distinguishing feature of this problem is the risk constraint that is used to limit the risk each vehicle runs.
(2) A library containing two sets of problem instances for the RCTVRP, some with known optimal solution, is generated.
(3) A mathematical formulation of the RCTVRP is developed and optimal solutions for small problem instances are found by using the IBM CPLEX solver.
(4) Efficient metaheuristic approaches to solve small, medium and large instances of the RCTVRP are presented, tuned using a statistical experiment, and then compared.

The remainder of the paper is organized as follows. In Section 2 the literature on vehicle routing in risk-prone situations is surveyed, and the concept of *risk constraint* is introduced. Section 3 outlines a mathematical formulation for the RCTVRP, while the different components of the metaheuristic approaches are described in Section 4. In Section 5, the algorithms are tested and computational results are reported. Section 6 presents some conclusions and suggestions for future research. A description of the sets containing the test instances, including the procedure that was used to generate them, can be found in Appendix A.

2. Risk constraint

Besides the "peripatetic" vehicle routing problems discussed earlier, the concept of risk has only received limited attention in the context of vehicle routing problems for the CIT sector, whereas it has been thoroughly analysed in the literature on transportation of chemical and hazardous materials (*hazmat*).

In the hazmat transportation literature many models have been developed in which a risk function is defined for each road section and safe routes are selected looking at the minimization of the operating costs. The risk function is in general based on the substance being transported, but also on the road characteristics (e.g., tunnels, road condition, light, traffic). See for example Androutsopoulos and Zografos (2012); Bianco, Caramia, Giordani, and Piccialli (2013); Reniers et al. (2010); Van Raemdonck, Macharis, and Mairesse (2013).

As defined by the Center for Chemical Process Safety (2008), risk can be seen as an index of potential economic loss, human injury, or environmental damage, that is measured in terms of both the incident probability and the magnitude of the loss, injury, or damage. The *risk* associated with a specific (unwanted) event can be expressed as the product of two factors: the likelihood that the event will occur (p_{event}) and its consequences (C_{event}). A risk therefore is an index of the "expected consequence" of the unwanted event.

$$R_{\text{event}} = p_{\text{event}} \cdot C_{\text{event}} \tag{1}$$

In case of hazmat, an undesirable event is an accident that results in the release of hazardous substances with severe consequences on the population in the neighbourhood of the incident. The consequences of the event depend on several factors such as the substance carried, the size of the population living near the accident, etc. The probability of an accident occurring depends on the type of substance transported and on the road characteristics such as lane width, number of lanes, etc. (see Milovanović, Jovanović, Živanović, & Žeželj, 2012 for further details). Another study also considers the influences of weather conditions on the accident probability (Akgün, Parekh, Batta, & Rump, 2007).

The definition of risk in Eq. (1) has many desirable features (additivity, linearity) that facilitate the solution process. As mentioned in Díaz-Ovalle, Vázquez-Román, De Lira-Flores, and Mannan (2013), the risk estimation always refers to specific scenarios and the attitude to risk of various decision-makers may differ. However, a comparison between the risk measures, that have been modelled in the field of hazmat transportation, as well as the possible attitudes towards risk, is beyond the scope of this paper. For a more elaborate discussion on risk measures, the reader is referred to Erkut and Ingolfsson (2005). In the remainder of our work we suppose that the decision maker has a risk-neutral attitude.

In the CIT sector, differently from the hazmat transportation, the goods being transported are not dangerous, but a robbery might generate two different types of unwanted consequences. The first type consists of the *foreseeable consequences* that are mainly linked to the loss of the cash/valuables being transported. The second type includes the *unforeseeable consequences* that are related to the criminal activity itself. An armed assault, e.g., might result in CIT personnel or third persons being seriously harmed. Therefore unforeseeable consequences

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