Omega 55 (2015) 73–80

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

Minimizing takeoff and landing risk in helicopter pickup and delivery operations☆

Irina Gribkovskaia [a], Oyvind Halskau [a], Mikhail Y. Kovalyov [b,*]

[a] Molde University College, The Norwegian School of Logistics, 6405 Molde, Norway
[b] United Institute of Informatics Problems, National Academy of Sciences of Belarus, Surganova 6, 220012 Minsk, Belarus

ARTICLE INFO

Article history:
Received 16 November 2013
Accepted 27 February 2015
Available online 6 March 2015

Keywords:
Combinatorial optimization
Dynamic programming
Routing
Scheduling
Risk

ABSTRACT

The problem of minimizing total helicopter passenger risk caused by takeoffs and landings is studied. There are passenger pickup and delivery demands to be satisfied at given points by flights starting and ending in the same heliport and visiting several points. For each point, the delivery demand is the number of passengers to be transported from the heliport to this point and the pickup demand is the number of different passengers to be transported from this point to the heliport. Each pickup and delivery demand must be satisfied in full by one flight. There are an upper bound on the number of flights and an upper bound on the helicopter passenger capacity. The objective function is a linear combination of the numbers of passengers involved in takeoffs and landings at visited points. A solution is characterized by the number of flights, sets of visited points and their sequences for all flights. Properties of optimal solutions are established. Several cases are proved NP-hard. A quadratic boolean programming formulation and two dynamic programming algorithms are suggested for the general case. Computer experiments demonstrated that they are able to solve real-life instances. Polynomial time algorithms are presented for special cases. Implementation of the suggested solutions into the real helicopter operations should decrease the number of fatalities.

1. Introduction

In many industries such as exploration and extraction of sea and land resources, military service, and tourism, people are transported by helicopters to and from their working places or places of interest located in hardly accessible areas. On one hand, this type of transportation is convenient but, on the other hand, it is risky because of helicopter accidents that happen from time to time. According to the data compiled by the National Transportation Safety Board (NTSB), an independent U.S. government agency, the total number of civil helicopter accidents recorded by this agency in 2004–2008 is 853, in 2008–2012 it is 712, and many of them include people fatalities or series injuries, see [10,8].

Transportation Safety Board of Canada [29] reports that from 2003 to 2012, there were 523 helicopter accidents in Canada and with Canadian helicopters outside Canada. Among them, the standing/taxiing phase totaled 45 accidents and 1 fatal accident, the takeoff phase totaled 66 accidents and 11 fatal accidents, the phase en route totaled 94 accidents and 30 fatal accidents, the phase manoeuvering totaled 110 accidents and 22 fatal accidents, the approach phase totaled 46 accidents and 10 fatal accidents, and the landing phase totaled 162 accidents and 9 fatal accidents. Thus, the takeoff, approaching and landing phases resulted in 52% of all accidents. Collision with terrain was the predominant event in fatal helicopter accidents from 2003 to 2012.

Nascimento et al. [21] observe that approaching and landing of helicopters traveling to offshore oil and gas platforms in Brazil cause great concern during the nighttime. Hinkelbein et al. [15] report that landing was the phase of flight most often associated with accidents for helicopter emergency medical service in Germany.

In this paper we study the problem of minimizing the total helicopter passenger risk caused by takeoffs and landings via a better composition of flights and their routing. In the problem, there are passenger pickup and delivery demands to be satisfied at given points by flights starting and ending in the same heliport. For each point, the delivery demand is the number of passengers to be transported from the heliport to this point and the pickup demand is the number of passengers to be transported from this point to the heliport. Each pickup and delivery demand must be satisfied in full by one flight. The flights have the same passenger capacity.

Qian et al. [23] suggest measuring the total helicopter passenger risk in terms of the total expected number of passenger fatalities. This approach is consistent with the recommendations of the International Association of Oil and Gas Producers [1], which state that

☆This manuscript was processed by Associate Editor Pesch.

* Corresponding author.
E-mail addresses: Irina.Gribkovskaia@hiMolde.no (I. Gribkovskaia), Oyvind.Halskau@hiMolde.no (O. Halskau), kovalyov_my@newman.bas-net.by (M.Y. Kovalyov).

http://dx.doi.org/10.1016/j.omega.2015.02.010
0305-0483/

the individual risk per journey, denoted as IR, can be estimated as

$$\mathrm{IR} = \mathrm{IR}(\mathrm{In-flight}) + \mathrm{IR}(\mathrm{takeoff\ \&\ landing}),$$

where

$$\mathrm{IR}(\mathrm{In-flight}) = \text{Accident frequency in} - \text{flight (per hour)} \times \text{Flight time (hours)} \times \text{Probability of fatal accident} \times \text{Probability of death in fatal accident}$$

and

$$\mathrm{IR}(\text{takeoff \& landing}) = \text{Accident frequency in takeoff \& landing (per flight stage)} \times \text{Number of flight stages per journey} \times \text{Probability of fatal accident} \times \text{Probability of death in fatal accident}.$$

The International Association of Oil and Gas Producers [1] recommends to use local data for the above model. Where local data are not available, the frequencies and probabilities recommended by this association are given in Table 1.

Consider a helicopter journey starting and finishing in a heliport, denoted as point 0, and visiting points $1,\dots,n$. Based on the above risk estimation model, we suggest that the total helicopter passenger risk associated with takeoffs and landings of this journey can be estimated as $\mathrm{TR} = \sum_{j=0}^{n}(w_j^{out}x_j^{out} + w_j^{in}x_j^{in})$, where w_j^{out} and w_j^{in} are given per passenger risk coefficients associated with takeoff and landing at point j, respectively, and x_j^{out} and x_j^{in} are numbers of passengers involved in these takeoff and landing, respectively, $j = 0, 1, \dots, n$.

Note that the risk coefficients may not necessarily be calculated as the accident frequency multiplied by the probability of fatal accident and probability of death in fatal accident. They can be any numbers that appropriately rank a relative per passenger risk associated with takeoffs and landings at points $j = 1,\dots,n$, because the aim is to find a decision which is relatively better than any other decision with respect to the total risk. The relative risk coefficients can be obtained from experts.

Given pickup and delivery demands, the total risk associated with takeoff and landing at the heliport does not depend on the number of flights or their routing. Therefore, we exclude heliport from further consideration and consider the problem of minimizing:

$$\mathrm{TR} = \sum_{j=1}^{n}(w_j^{out}x_j^{out} + w_j^{in}x_j^{in}).$$

Studies of the helicopter routing problems with the objective of minimizing the total passenger risk were initiated by Qian et al. [23–25]. Qian et al. [23,24] studied various routing policies for minimization of the total in-flight and takeoff and landing risk.

Table 1
Offshore helicopter transport flight accident data for risk estimation model [1].

Region	Flight Phase	Frequency	Unit	Probability of fatal accident	Probability of death in fatal accident
North Sea	In-flight	8.5×10^{-6}	Flight hour	0.20	0.85
	Takeoff & landing	4.3×10^{-7}	Flight stage	0.17	0.48
Gulf of Mexico	In-flight	8.5×10^{-6}	Flight hour	0.33	0.59
	Takeoff & landing	2.7×10^{-6}	Flight stage	0.24	0.49
Rest of World	In-flight	8.5×10^{-6}	Flight hour	0.74	0.87
	Takeoff & landing	2.7×10^{-6}	Flight stage	0.24	0.49

Computer experiments in Qian et al. [24] demonstrate that for the considered instances the most essential component of the risk associated with offshore transportation is the takeoff and landing risk. Qian et al. [25] concentrated solely on minimization of the takeoff and landing risk. They considered only pickup operations or only delivery operations and demonstrated relations of this case with the bin packing and scheduling problems. All three publications assumed equal risk coefficients at all points.

The risk minimizing helicopter routing problem can be classified as *One-to-Many-to-One Pickup and Delivery Vehicle Routing Problem (1-M-1 PDVRP)* with multiple vehicles, combined (pickup and delivery) demands and Hamiltonian routes. There exists a vast body of the literature on the problem 1-M-1 PDVRP, see surveys of Berbeglia et al. [5] and Parragh et al. [22], and recent results of Tütüncü et al. [30], Battarra et al. [4], Karaoglan et al. [16], Nagy et al. [20] and Wassan and Nagy [31]. Studies of the single vehicle version of this problem, called *Pickup and Delivery Traveling Salesman Problem*, were initiated by Mosheiov [19]. The traditional criterion in the problem 1-M-1 PDVRP is the travel cost or distance minimization. Therefore, the results for the problem 1-M-1 PDVRP cannot be directly used for solving the risk minimizing helicopter pickup and delivery routing problem.

Moreno et al. [18] and Menezes et al. [17] considered minimization of the number of flights and the total number of offshore landings as the factors to improve helicopter flight safety. Bae and Lee [2] suggest to use Imprecise Data Envelopment Analysis for risk evaluation and risk allocation applied to operations of Korean Army helicopters.

In this paper we analyze computational complexity and derive solution algorithms for the problems of determining helicopter flight loads and routes with the purpose of minimizing the total passenger risk in the cases of a single flight (Section 2) and at most m flights (Section 3) of the same passenger capacity, provided that the given passenger pickup and delivery demands are satisfied. Solution approaches include a quadratic boolean programming formulation and two dynamic programming algorithms for the most general case, and problem specific polynomial time algorithms for several special cases. Section 4 describes results of computer experiments with the dynamic programming algorithms. The paper concludes with a summary of the results and suggestions for future research.

For each problem or its special case we introduce notation followed by the problem formulation, and then describe our results.

2. One flight

In this section it is assumed that the pickup and delivery demands at the points must be satisfied by a single helicopter flight.

Problem 1-Min-Risk: There are points of a set $N = \{1,\dots,n\}$. Point $j \in N$ has the delivery and pickup demands of d_j and p_j passengers, respectively, to be satisfied by a single helicopter flight which visits each point exactly once. For each point j, d_j passengers must be transported from the heliport to the point, and different p_j passengers must be transported from the point to the heliport by the same flight. The total passenger risk at point j is calculated as $w_j^{in}x_j^{in} + w_j^{out}x_j^{out}$ where w_j^{in} and w_j^{out} are the per passenger risk coefficients associated with the landing and takeoff, respectively, at this point, and x_j^{in} and x_j^{out} are the numbers of passengers involved in the corresponding landing and takeoff. The problem is to find a helicopter route such that all the delivery and pickup demands are satisfied and the total passenger risk at all points is minimized. We assume that all w_j^{in} and w_j^{out} are strictly positive rational numbers and that all p_j and d_j are non-negative integer numbers.

Denote $D(N) = \sum_{j=1}^{n} d_j$ and $P(N) = \sum_{j=1}^{n} p_j$. Since the helicopter leaves the heliport with $D(N)$ passengers and arrives in the heliport