A three-stage relief network design approach for typhoon disasters considering time-dependent uncertainty

Jing Li[1, 2], Feng Chu[1], Che Ada[2]
[1] Laboratory IBISC, Univ Évry, Université Paris-Saclay, Évry, France
lijing2020@mail.nwpu.edu.cn, feng.chu@univ-evry.fr
[2] School of Management, Northwestern Polytechnical University, Xi'an, China
ache@nwpu.edu.cn

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1 Introduction

With fast urbanization and an exponential increase in the global population, the risk of exposure to natural disasters has grown significantly over the past years [1]. To minimize the damage caused by natural disasters, disaster relief management has attracted the attention of both decision-makers and researchers over the last few years [2, 3]. As stated in [4], uncertainty is unavoidable in disaster relief management. But the characteristics of different natural disasters are inherently different. The main difference between predictable and unpredictable disasters is their forecast lead time. An unpredictable disaster such as an earthquake can only be detected a few minutes in advance with current technology, while a predictable disaster such as a typhoon can be forecasted for a few days. When a typhoon develops, the warning information is constantly updated. Thus, the degree of uncertainty about typhoons can be regulated based on updated warning information, and the uncertainty is time-dependent [5].

In this study, we investigate a three-stage relief network design problem in the context of typhoon disasters considering time-dependent uncertainties simultaneously. The rescue decisions before, during the typhoon warning period, and after the typhoon landfalls are made comprehensively. A novel three-stage nonlinear robust optimization (3NRO) model is then formulated. To make the 3NRO model computationally tractable, we further develop a deterministic equivalent (DE), which can be solved by commercial solvers directly. A case study demonstrates the superiority of the proposed model.

2 Problem description

In this study, we address the rescue problem for typhoons that are more frequent and severe in recent years due to climate change. The aim of the work is to design a new time-dependent three-stage relief network design model to aid decision-makers in taking efficient actions for time-varying typhoons. The relief network we study is composed of the following four-tier: Major Distribution Centers (MDCs), Pre-staging areas (PSAs), Shelters(SHs), and potential disaster-affected points (PDPs). We assume (1) MDC locations are given, and the amount of available relief supplies prepositioned at MDCs is known; (2) There are two modes of transportation from MDCs to PSAs, ground and air. Air freight is less time-consuming but more expensive. (3) The sets of candidate locations of PSAs and SHs and their opening cost are given. Moreover, the capacities of a PSA and a SH are limited.

In our problem, facility locations including PSAs and SHs are determined before warning information is issued, and emergency supplies deployment and evacuation are decided during the disaster warning period, while emergency supplies are distributed after typhoon makes landfall. Besides, time-dependent uncertainty characteristics of typhoons' intensity and trajectory are considered simultaneously. They are described by using budget uncertainty sets [6], [7]. Generally speaking, the closer to the landfall time of the typhoon, the more accurate the typhoon forecast and the less degree of uncertainty in the uncertainty set. The objective is to minimize the total costs, involving the fixed costs of opening facilities, the rescue costs of emergency supplies deployment, distribution and people evacuation, and the penalty costs of unsatisfied demands. Since we find optimal rescue solutions under the worst case and consider three-stage rescue decisions in an integrated manner, the proposed model contains a "min-max-min-max-min" structure. The multilevel objective function makes the proposed model nonlinear.

3 Solution method

The proposed 3NRO model is a nonlinear one and cannot be solved by commercial solvers directly. To overcome the obstacle, two properties of the model are first derived, thereby reducing the number of variables and constraints in the model. After that, according to the saddle point theorem and the strong duality theorem, a mixed-integer linear programming DE model is developed, which can be solved directly with commercial solvers.

4 Conclusion and perspective

We comprehensively address the three stages of rescue decisions considering time-dependent uncertainty in the context of typhoon disasters. Based on this, we construct a novel three-stage nonlinear robust optimization (3NRO) model. We further develop a deterministic equivalent (DE) model to make the 3NRO model computationally tractable. A case study of Guangdong Province, a typhoon-prone region in China, is conducted to demonstrate that (1) integrating three-stage decisions can improve rescue efficiency; (2) inappropriate models can introduce huge latent risks to disaster managers; (3) the proposed DE model has better computational performance compared to the primal 3NRO model. In the near future, we will focus on how to develop an efficient algorithm for DE model.

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