Journal of Loss Prevention in the Process Industries 33 (2015) 29–38

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

# A transportation-location problem model for pedestrian evacuation in chemical industrial parks disasters

Yang Shen [a, b], Qingsong Wang [a, *], Weigang Yan [a], Jinghong Wang [a]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, China
[b] Rudong Coastal development zone of Jiangsu, Rudong, 226407, China

ARTICLE INFO

*Article history:*
Received 19 December 2013
Received in revised form
6 November 2014
Accepted 15 November 2014
Available online 17 November 2014

*Keywords:*
Location problem
Emergency management
Human vulnerability
Multi-objective model

ABSTRACT

A successful emergency management for chemical industrial parks (CIPs) accidents includes the route and shelter selection. Both of them are based on the collection of chemicals, atmosphere, geographic and population databases of CIPs. This decision process can be considered as a kind of transportation-location problem (TLP). In this paper, a conceptual model of emergency decision system for TLP of CIPs has been reported and a new multi-objective TLP model of pedestrian evacuation has also been proposed. The model includes sub-criteria, and the affected areas are categorized into a priority hierarchy based on human vulnerability model (HVM). The model can be used to design shelter places and guide the evacuation of the affected people. Besides, it can maximize the total time satisfaction level of evacuees combined with the routes passable probabilities. Finally, a case study shows that this model is flexible and applicable to various scenarios and risk measures.



## 1. Introduction

In recent years, chemical industrial parks (CIPs) have become one of the mainstreams of international development and a new developmental mode in the China's chemical industry. While CIPs can promote the development of the regional economy and chemical industry, it also poses new safety issues. Toxicant leakage is a main type of accidents in CIPs. In an event of accident, toxicant will not only pollute the environment, disturb the ecosystem, but also bring tremendous injuries to the safety of local workers and residents. A successful emergency management can reduce the damage to these people significantly.

Two important factors in emergency decision are the location of the shelters and the evacuation routes for affected zones. The decision-making process is often classified as an integrated location-routing problem (LRP). However, for a long time, most of literature have addressed the location problem (LP) and the routing problem (RP) separately. These two aspects of the LRP are closely interrelated, as shelter locations directly influence the routing options available, and available routes affect the locations of potential shelter in return. Maranzana (1964) proposed an algorithm applicable to the problem of location supply points optimally with respect to transportation cost, which was considered as the first work on the LRP. Gábor Nagy and Saïd Salhi (2007) provided an excellent invited review of location-routing problem and defined the LRP as "location planning with tour planning aspects taken into account". According to their definition, Maranzana's algorithm is not a location-routing problem (strictly speaking, it incorporates shortest-path, rather than vehicle-routing problems into a locational problem). Besides, they classified this problem as the transportation-location problem (TLP). TLP (Nagy and Salhi, 2007) combines the problem of locating facilities with that of transporting goods between supply and demand points. Each origin-to-destination route is a path (not necessarily a simple path) through the facilities to be located. This problem is also known as the path location-routing problem (PLRP) and especially frequently occurs in hazardous material transportation (Clark and Besterfield-Sacre, 2009; Verter and Kara, 2001).

TLP models have been investigated in detail resulting in abundant literature. These models integrate the discrete location problem (LP) and routing problem (RP). The classical LP is p-median problem selecting the best p sites among a range of possible locations with the objective of minimizing total demand-weighted travel distance between demand nodes and facilities. Other objectives considered for LP are minimizing fixed costs of selected facilities (set covering problem), maximizing the coverage of

* Corresponding author.
*E-mail address:* pinew@ustc.edu.cn (Q. Wang).

http://dx.doi.org/10.1016/j.jlp.2014.11.008
0950-4230/

**Nomenclature**

| | |
|---|---|
| $f(t_{ij})$ | time satisfaction function |
| $L_i$ | maximal time under which the decision is very successful (s) |
| $U_i$ | minimal time beyond which the damage to the individual's health is unacceptable (s) |
| $t_{ij}$ | actual time the evacuees in area $i$ taken to arrive at the shelter $j$ (s) |
| $Y$ | probability to a measure of the percentage of the vulnerable affected resource |
| $D$ | independent variable as a function of the factor that causes injury or damage to the vulnerable resource $[(ppm)^n s$ or $(kg/m^3)^n s]$ |
| $a$, $b$ | regression coefficients which are generally estimated from empirical data |
| $c$ | concentration of the toxic gas (ppm or $kg/m^3$) |
| $n$ | a constant which is a function of specified species |
| $t$ | the exposure time (s) |
| $I$ | the radiation intensity ($W/m^2$) |
| $P_e$ | peak static overpressure (Pa) |
| $Y_S$ | social vulnerability |
| $Y_{Si}$ | total human venerability of area $i$ |
| $V_{soc}$ | social indicators |
| $U_{ij}$ | road risk utility |
| $x_{ij}$ | blocking risk of link $i$-$j$ |
| $p_{ij}$ | passable probability of link $i$-$j$ |
| $p_i$ | total passable probability of area $i$ |
| $p_{min}$ | minimum passable probability in evacuation network |
| $p_{max}$ | maximum passable probability in evacuation network |
| $\xi_{ij}$ | structure importance of link $i$-$j$ |
| $T_{ij}$ | total evacuation time if link $i$-$j$ cannot be passed through (s) |
| $T$ | evacuation time when link $i$-$j$ is available (s) |
| $\tau_{ij}$ | ratio of the time extension when link $i$-$j$ is not available and the maximum time extension |
| $u_i$ | total measured passable value of area $i$ |
| $k$ | number of evacuation routes to shelter places in area $i$ |
| $Z_{ij}$ | a decision variable, if the evacuees in area I are evacuated to shelter $j$, then $Z_{ij} = 1$, otherwise $Z_{ij} = 0$ |
| $p$ | number of shelter places |
| $X_j$ | $X_j = 1$ if the shelter place located in $j$, otherwise $X_j = 0$ |
| $w_T$, $w_L$ | weight coefficients determined by the decision makers |
| $u_i^1$ | total utility of the shortest route for area $i$ |
| $u_i^2$ | second shortest route for area $i$ |
| $V_1$ | population indicator on social vulnerability |
| $V_2$ | indicator of distance to hazard source on social vulnerability |
| $M$ | number of hazard sources that affected region $i$ |

demand (maximal covering problem), and minimizing maximum distance between demand–facility pairs (p-center problem). The maximal covering location problem (MCLP) has been approved to be the best method to solve LP. More details can be found in (Berman and Krass, 2002; Current et al., 2002; Marianov and Serra, 2002). Table 1 is a summary of classic coverage problems. Additionally, the most classical RPs are the shortest path problems (Yamada, 1996) and the K-shortest path problems (Yen, 1971).

The model proposed here aims to determine the locations of shelter places combined with the evacuation routes. That is, this model can be classified as an integrated transportation-location model (TLP), which has been proved to be very applicable in practice and is not just a purely academic construct. As LP and RP are often based on multiple criteria, TLP is also a multiple criteria problem and the cost minimization is obviously one of these criterions. Thus, the number of shelters is limited. In this model, the

**Table 1**
Summary of location problems.

| Location problem | Definition | Objective function |
|---|---|---|
| p-median (Hakimi, 1965) | Selecting the best p sites among a range of possible locations with the objective of minimizing total demand-weighted travel distance between demand nodes and facilities | $Min \quad Z = \sum_i \sum_j h_i d_{ij} Y_{ij}$<br>$s.t \quad \sum_j Y_{ij} = 1 \quad \forall i$<br>$\sum_j X_j = P$<br>$Y_{ij} - X_j \le 0 \quad \forall i, j$<br>$X_j = 0, 1 \quad \forall j$<br>$Y_{ij} = 0, 1 \quad \forall i, j$ |
| p-center (Suzuki, 1996) | Selecting the best p sites minimizing maximum distance between demand–facility pairs | $Min \quad r$<br>$s.t \quad \sum_{j \in J} h_i d_{ij} Z_{ij} \le r$<br>$\sum_{j \in J} Z_{ij} = 1$<br>$Z_{ij} \le y_j$<br>$\sum_{j \in J} y_j = p$<br>$Z_{ij} = 0, 1 \quad y_j = 0, 1$ |
| SCLP (Sahraeian and Kazemi, 2011) | Minimum total number of facilities or construction cost of service station on the premise that all demand nodes are covered | $Min \quad \sum_j f_i x_j$<br>$s.t \quad \sum_j C_{ij} x_j \ge 1$<br>$x_j = \begin{cases} 1 \\ 0 \end{cases}$ |
| MCLP (Davari et al., 2013) | Selecting the best location of shelter places maximizing the coverage of demand | $Max \quad \sum_j h_i Z_j$<br>$s.t \quad \sum_j C_{ij} x_j \ge Z_i$<br>$\sum_j x_j = P$ |