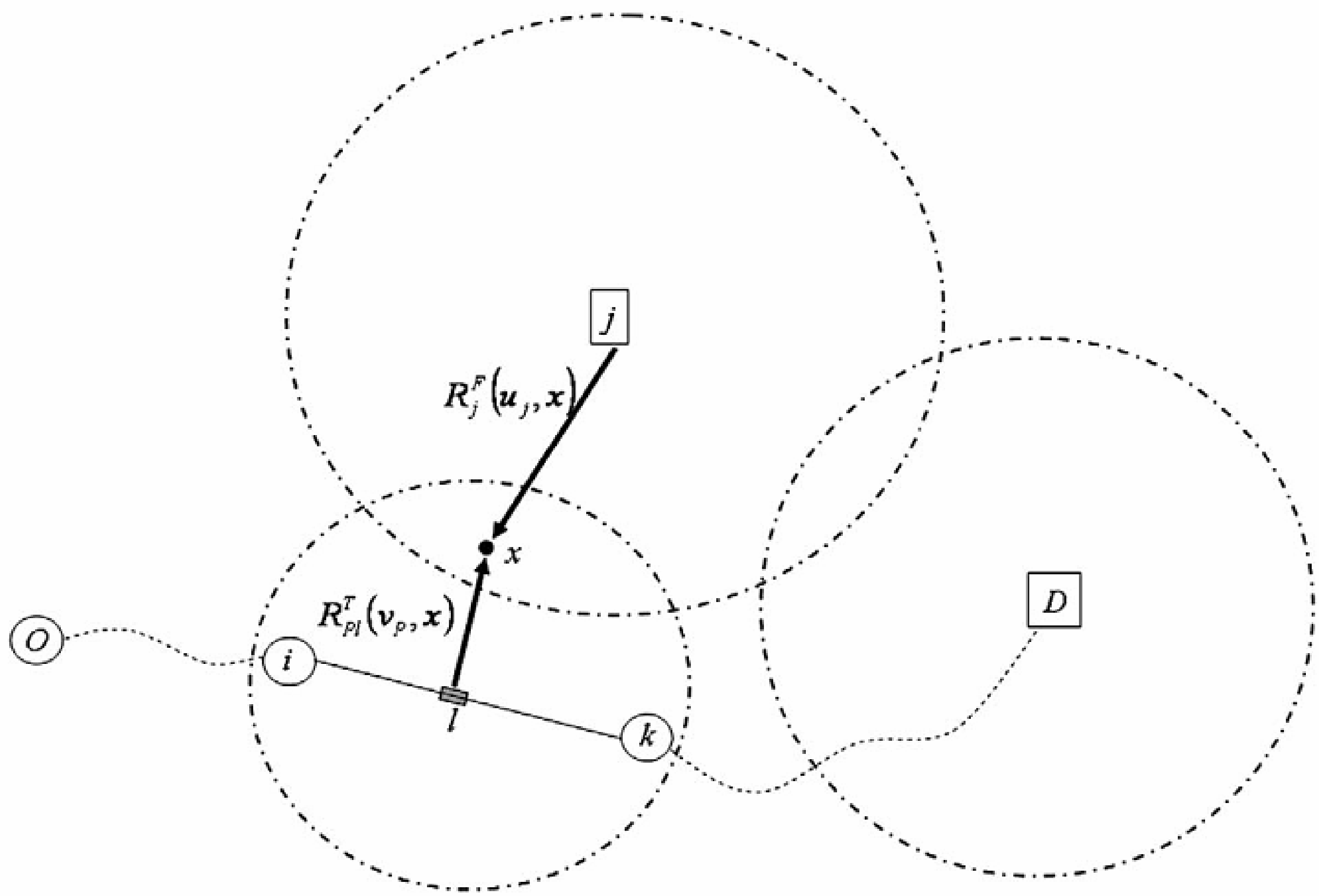
Models that combine undesirable facility location and hazmat transportation

- *Hazmat shipments often originate from facilities that themselves are potentially harmful to public and environmental safety*, such as *petroleum refineries* or *nuclear power plants chemical industry plants, warehouses for explosives, petroleum products,…*. Also, the destinations of hazmat shipments can be noxious facilities such as *gas stations* and *hazardous waste treatment centers*.
- The location decisions pertaining to such facilities have a considerable effect on the routing of hazmat shipments. Therefore, integration of facility location and routing decisions can be an effective means to mitigate the total risk in a region where hazmats are processed and transported.
- It is interesting to note that, ***in general, location decisions are considered strategic, whereas routing decisions are dealt with at the tactical level***. However, the risk constitutes a coupling factor for these decisions in the context of dangerous goods. We refer the reader to Erkut and Neuman (1989) and Cappanera (1999) for extensive surveys of the location-only literature dealing with undesirable facilities.
- The *location–routing problem (LRP) involves determining the optimal number, capacity, and location of facilities as well as the associated optimal set of routes (and shipping schedules)* to be used in serving customers.

- The distribution of goods from the facilities to the customers can be on a full-truck load or less than full-truck load basis. In the latter case, routes involving multiple customers are commonly used.
- From the solution method perspective, the LRP is NP-hard and offers a variety of challenges. The literature addressing LRP with different real-world applications has evolved since the late 1960s. Christofides and Elon (1969) were among the first to consider LRP with multiple customers on each route. The literature surveys on LRP include Madsen (1983), Balakrishnan et al. (1997), and Min et al. (1998).
- Two types of risk need to be taken into account in integrating location and routing decisions pertaining to hazmat shipments: **transport risk, R^T**, and **facility risk, R^F**. Figure illustrates these two types of risk.
- An individual at point x is exposed to
  - a transport incident on a nearby route segment $\boldsymbol{l}$ of a path $\boldsymbol{P}$ that involves a vehicle carrying volume $\boldsymbol{v_P}$ and
  - an incident at the hazmat treatment center at site $\boldsymbol{j}$ with capacity $\boldsymbol{u_j}$.
- The **transport risk**, $\boldsymbol{R^T_{Pl}\ (v_P,x)}$, can be determined as a function of the undesirable consequence at point $\boldsymbol{x}$, taking into account the impact zone of a hazmat incident on segment $\boldsymbol{l}$ (see previous sections), and the estimated incident probability.
- The facility risk, $\boldsymbol{R^F_j\ (u_j,\ x)}$, can be determined in a similar way, with site $\boldsymbol{j}$ replacing the route segment $\boldsymbol{l}$.



Individual risk at point x due to transportation and processing of dangerous goods (adapted from List and Mirchandani, 1991).

- Let ***O*** and ***D*** denote sets of origins and destinations, respectively, $\boldsymbol{P_{OD}}$ denote the set of all utilized paths for each ***O–D*** pair ($\boldsymbol{O \in O}$ and $\boldsymbol{D \in D}$), and ***L*** denote the set of hazmat facility locations. Assuming additivity of risk, the individual risk at point ***x*** can be determined as

$$R(x) := \sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} \sum_{l \in P} R^{\mathrm{T}}_{Pl}(v_P, x) + \sum_{j \in \mathbf{L}} R^{\mathrm{F}}_{j}(u_j, x).$$

- Let ***A*** denote the region of interest and ***POP(x)*** denote the population density at point $\boldsymbol{x \in A}$. The total risk in ***A*** is

$$R(A) = \int_{x \in A} R(x) POP(x)\, \mathrm{d}x.$$

- Now consider a location–routing problem where ***L = D*** (e.g., storage locations for spent nuclear fuel shipments). Let $\boldsymbol{V_O}$ denote the hazmat volume at $\boldsymbol{O \in O}$ (e.g., a nuclear power plant) that needs to be transported, and let $\boldsymbol{u_D}$ denote the capacity of a hazmat treatment facility at site D$\in$ **D**.
- Note that ***D*** and $\boldsymbol{P_{OD}}$ now represent the *sets of candidate locations for hazmat treatment facilities* and the *set of potential paths for each origin–destination pair*, respectively. The set $\boldsymbol{P_{OD}}$ may represent the set of available routes on the hazmat road network designated by the government.

- We define two types of variables:
  - binary location variables y_D, where

$$y_D = \begin{cases} 0, & \text{if a new hazmat treatment facility is located} \\ & \text{in site } D, \\ 1, & \text{otherwise,} \end{cases}$$

  - nonnegative continuous flow variables v_P representing the quantity of hazmat shipped along path P.
- Thus, the total risk in region A is

$$R(A) := \int_{x \in A} \Bigg(\sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} \sum_{l \in P} R^{\mathrm{T}}_{Pl}(v_P, x) + \sum_{D \in \mathbf{D}} R^{\mathrm{F}}_{D}(u_D, x) y_D \Bigg) POP(x)\, \mathrm{d}x.$$

- In addition to the total risk, the costs (i.e., transportation, operation, and fixed costs) should be also minimized.
- Let c^T_P denote the transportation cost per unit volume of hazmat along path P, c^F_D denote the (annualized) installation cost and c^O_D denote the unit operation cost of a hazmat treatment facility at site D. The total cost, TC, is determined as

$$TC := \sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} c^{\mathrm{T}}_{P} v_P + \sum_{D \in \mathbf{D}} \Bigg(c^{\mathrm{F}}_{D} y_D + c^{\mathrm{O}}_{D} \sum_{O \in \mathbf{O}} \sum_{P \in \mathbf{P}_{OD}} v_P \Bigg)$$

- Also, equity in the spatial distribution of risk due to the location and routing decisions can be a relevant objective. Risk equity can be enforced, for example, by minimizing the maximum individual risk in the region, i.e.,

$$\overline{R}(A) := \max_{x \in A} R(x).$$

- Hence, a mathematical programming formulation of the capacitated LRP to minimize the total risk and total cost and to force the risk equity can be constructed as follows:

$$\min \; R(A) \tag{5.1}$$

$$TC \tag{5.2}$$

$$\overline{R}(A) \tag{5.3}$$

subject to:

$$\sum_{D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} v_P = V_O, \quad \text{for all } O \in \mathbf{O}, \tag{5.4}$$

$$\sum_{O \in \mathbf{O}} \sum_{P \in \mathbf{P}_{OD}} v_P \leqslant u_D y_D, \quad \text{for all } D \in \mathbf{D}, \tag{5.5}$$

$$\overline{R}(A) \geqslant \sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} \sum_{l \in P} R^{\mathrm{T}}_{Pl}(v_P, x) + \sum_{D \in \mathbf{D}} R^{\mathrm{F}}_{D}(u_D, x) y_D, \quad \text{for all } x \in A, \tag{5.6}$$

$$y_D \in \{0, 1\}, \quad \text{for all } D \in \mathbf{D}, \tag{5.7}$$

$$v_P \geqslant 0, \quad \text{for all } P \in \mathbf{P}_{OD} \text{ and } O\text{–}D \text{ pairs}, \; O \in \mathbf{O}, D \in \mathbf{D}. \tag{5.8}$$

- Constraints (5.4) ensure that all hazmat generated must be shipped out of the origins, whereas constraints (5.5) stipulate that if a facility at location D is open (i.e., $\boldsymbol{y_D = 1}$), then total quantity of hazmat to be treated at D cannot exceed the pre-specified capacity of the facility. Constraints (5.6) are used to incorporate the risk equity.
- ***It is evident from the above model that the hazmat LRP is multi objective by nature***. The surveys by List et al. (1991), Boffey and Karkazis (1993),and Cappanera et al. (2004) observed that *literature on hazmat LRP is sparse*.
- ***Shobrys (1981)*** is the *first study on hazmat LRP with a focus on selecting routes and storage locations for spent nuclear fuel shipments*. A decomposition approach is used to separate the routing problem from the location problem.
- *Two routing objectives are minimized; ton-miles and population exposure tons*. The associated bi-objective shortest path model identifies a set of Pareto-optimal paths between each waste source (origin) and each candidate storage site (destination). The weighted costs associated with each Pareto-optimal path determine the cost coefficients of the p-median problem that is used to select the storage site.
- ***Zografos and Samara (1989)*** *considered an LRP with three objectives, namely minimization of transport risk, minimization of travel times, and minimization of disposal risk*, to establish locations of a given number of waste treatment facilities and determine the associated shipment routes. Their model requires that the hazardous waste at each population center must be disposed of entirely. Each population center is assigned to its nearest disposal facility.

- Moreover, links of the transportation network are capacitated. Pre-emptive goal programming is used to generate solutions under a few different scenarios.
- ***List and Mirchandani (1991)*** *proposed a hazmat LRP model that simultaneously considers total transportation and treatment risk, total transportation cost, and risk equity*. Risk equity is enforced by minimizing the maximum consequence per unit population for all mutually disjoint zones of the transportation network. Their formulation served as a basis for the model in (5.1)–(5.8).
- However, the List and Mirchandani model is more general since it allows for different types of hazardous materials and treatment technologies. This model assumes that the impact to point $\boldsymbol{x}$ in a zone $\boldsymbol{Z}$ from a vehicle incident is inversely proportional to the square of the Euclidean distance between the vehicle and point $\boldsymbol{x}$, and the impact is directly proportional to the volume $\boldsymbol{v_P}$ being shipped regardless of material. Hence, the transport risk faced by an individual at point x is determined as

$$R^{\mathrm{T}}_{Pl}(v_P, x) := \alpha v_P \int_{l \in P} \|l - x\|^{-2} c(x)\pi(l)\,\mathrm{d}l,$$

  where $\boldsymbol{\alpha}$ is a constant of proportionality, $\boldsymbol{c(x)}$ is a likelihood of impact at point $\boldsymbol{x}$, and $\boldsymbol{\pi(l)}$ is the probability of an incident at road segment $\boldsymbol{l}$. The facility risk from an incident at a hazardous waste treatment facility at site $\boldsymbol{j}$ of waste type $\boldsymbol{w}$ with treatment technology $\boldsymbol{t}$ and volume $\boldsymbol{u_{jwt}}$, $\boldsymbol{R^F_{jwt}(u_{jwt}, x)}$,is determined in a similar way.
- However, their facilities have unlimited capacity and the total cost of establishing treatment facilities is bounded by a budget constraint.

- Uncertainty is considered in constructing the risk formulations, but it is not incorporated in solving the example case. Instead, the expected number of fatalities is used to calculate the risk. The LRP problem is solved using LINDO.
- The weighted sum technique is used to study the tradeoffs among the objectives in identifying the transportation routes, locating the hazardous waste treatment facilities, and choosing the treatment technologies.
- ***ReVelle et al. (1991)*** *developed a combined discrete location–routing model for shipments of spent nuclear fuel that minimizes both transportation cost and perceived risk*. As in Shobrys (1981), the transportation cost is measured in ton-miles, and the perceived risk is measured using population exposure as people-tons. The total people-ton of an arc is the product of the number of people within a certain bandwidth on the arc and the tons of hazardous waste shipped on that arc.
- The problem is solved in two stages. In the first stage, a weighted sum of the arc distance and the number of people in the impact area around that arc (called hybrid distance) is calculated for every arc in the network. Floyd's shortest path algorithm is used to generate (hybrid) shortest paths for all origin–destination pairs.
- In the second stage, the location problem is modeled as a p-median problem, where the coefficients of the objective function are calculated by taking the product of the tons of spent fuel at the origin and the hybrid shortest distance from the origin to the destination.
- ***Stowers and Palekar (1993)*** proposed a *bi-objective network LRP with a single facility and a single commodity*. In a network LRP, the waste facility can be located anywhere on

the network. Two objectives are considered, namely minimizing the total exposure (mini sum) and minimizing the maximum exposure (mini max).

- The total exposure to a node or to an arc of the network is represented as a convex combination of location exposure and travel exposure, where the impact area is modeled as a danger circle.
- ***Giannikos (1998)*** proposed a multi objective model for a discrete hazardous waste LRP that minimizes the following four objectives:
  - (1) total transportation cost and fixed cost of opening the treatment facilities;
  - (2) total perceived risk due to the shipment of hazardous waste;
  - (3) maximum individual risk (to force the risk equity); and
  - (4) maximum individual disutility due to the treatment facilities.
- The disutility imposed on a population center ***i*** by the establishment of a treatment facility at site ***j*** is a function of the capacity of facility ***j*** and the distance between ***i*** and ***j***. The total disutility at population center ***i*** is obtained by adding the disutilities imposed upon ***i*** by all treatment facilities. A weighted goal programming technique is used to solve the problem.
- ***Cappanera et al. (2004)*** presented a single objective LRP model that minimizes the total transportation and facility establishment costs. In their model, an arc formulation is given instead of a path formulation as in (5.1)–(5.8).Their model includes constraints that require both routing and population exposures for each affected site to remain within

given threshold values. Arcs of the network are incapacitated, but the facilities are capacitated. By dualizing the capacity constraints, the LRP is decomposed into location and routing sub problems to obtain a lower bound. To find the upper bounds, two Lagrangian heuristics, called the Location–Routing heuristic and Routing–Location heuristic, are proposed.

Note that almost all existing models for hazmat LRP are static and deterministic. Only the model of List and Mirchandani (1991) considers different types of hazmats and technology selection for hazmat treatment facilities as well as uncertainty in problem parameters.
The lack of multiple hazmat models that consider stochasticity in a time-dependent environment constitutes an area for further LRP research.