物流系统分析
Logistics System Analysis

第 11 周　带转运的一到多配送问题（1）—新问题
One-to-Many Distribution with Transshipments — New problems

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目 录 |Outline

- A transshipment is the act of taking an item out of a vehicle and loading it onto another. Typically, transshipments take place at fixed facilities, i.e., terminals.
- For modeling purposes, these can be viewed as a set of berthing gates connected by an internal sorting, storage and transfer system. The berthing gates accommodate the vehicles while they are being loaded and unloaded; the sorting-storage-transfer system moves the items from one vehicle to another. 从建模的角度，这些中转枢纽可视为一系列的泊位闸门。这些闸门由内部的“分拣-储存和转运系统”相连接。车辆在装卸货时由闸门处理，分拣-储存和转运系统负责将货物在车辆上移动

中转枢纽的职能

- Although many different technologies exist depending on the freight that is being moved, conceptually this makes little difference. (The internal transfer system, for example, can use: carts on rails 轨道运送小车, forklift trucks 叉车, conveyor belts 传送带, idler rollers 传送支持滚轮 or gravity chutes 重力滑槽.) The emphasis at efficient terminals is on moving the freight quickly with little allowances made for long term storage.
- But if there is a need to accommodate seasonal fluctuations in demand, or to hold inventories closer to the points of demand when response time is critical and demand cannot be anticipated, **terminals can also provide a warehousing function**.

We study

- qualitative properties of **near-optimal systems**, which allow the problem to be treated analytically;
- how **systems** where items are transhipped no more than once can be **designed**, using an uncomplicated scenario as an illustration.
- modifications to the procedure able to capture the following complicating features: **schedule synchronization**, **variable and uncertain demand**, **asymmetric strategies**, as well as **constraints on locations, routes and schedules**.
- multiple transshipment problem.
- how to computerize the design guidelines

目 录 |Outline

主要规划

- After reviewing the reasons for transshipments in one-to-many logistics systems, we will show that finding the **ideal spatial arrangement of terminals is the critical step in designing a system**.
- The rest is easy because, for a given arrangement, there is a well defined set of **item paths**, **vehicle routes**, and **schedules** that (nearly) minimize total cost.

何时发生转运

- Items are often transshipped when there is an incentive to change transportation modes or vehicle types.
- While **geographical barriers** such as coastlines invariably require a modal change (e.g. at seaports), purely **economical considerations** may also encourage changes in vehicle type.

- We realized that vehicles should be filled to capacity for the distribution of "cheap" freight; i.e., where pipeline inventory cost is negligible compared to the other logistic cost components.
- Because the optimal cost was a decreasing cost of v_{max}, we argued that (if there is a choice) one should use the largest vehicles that the local roads and the destination loading/unloading facilities can accommodate.
- If vehicle size is limited in the immediate vicinity of the customers, transshipments at terminals in the general neighborhood of the customers may be attractive, as this could allow larger vehicles to feed the terminals. 假设两个直接相邻的两个顾客之间对车辆容量限制不同，则在二者之间设置中转枢纽比较有利，因为可以用大容量的车辆满足枢纽需求

Effect of a transshipment on vehicle-miles traveled

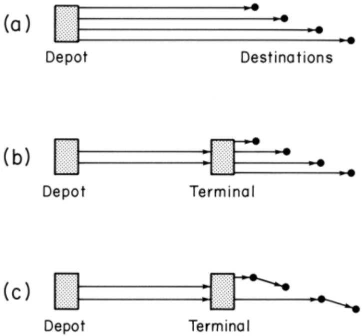
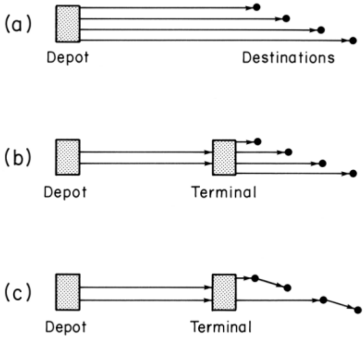


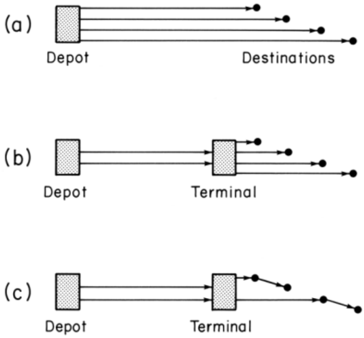
Figure (a) depicts one origin (the depot) and four customers that receive direct service once a day. Each daily trip is represented by one arrow joining the beginning and end of the trip. Let us assume that the pattern of the figure is optimal for the situation at hand, and that the trips are made by **delivery vans**, due to the small access roads leading to the customers.

Effect of a transshipment on vehicle-miles traveled



- If a terminal is introduced, the transportation cost can be reduced without changing the service frequency to the customers (i.e. the waiting cost at the destination).
- The depot-to-terminal roads could accommodate trucks, and terminal-to-destination roads could be served by vans. $\text{Capacity}_{\text{truck}} = 2 \times \text{Capacity}_{\text{van}}$. Only 2 trucks will be dispatched every day. Destinations can still be served daily by vans from the terminal
- The transportation cost can be cut by a factor of ≈ 2 while the holding costs at the destinations keep unchanged

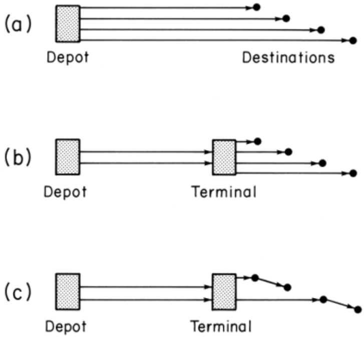
Effect of a transshipment on vehicle-miles traveled



- On the other hand, introducing a terminal may increase holding cost at the origin — items now leave the origin in larger batches — and introduces new handling and holding costs at the terminal.
- Whether the distribution scheme of Figure (b) is advantageous will depend on the magnitude of the transportation cost savings, which grow with **the distance** between the terminal and the depot, and with **the size difference** between vehicles delivering to the terminal and the customers.

- Recall that pipeline inventory considerations, in addition to operating restrictions such as the duration of a work shift, may **restrict delivery route length**; very valuable items should not be delivered on many-stop routes.
- A benefit from transshipments may be derived even if, due to route length limitations, vehicles cannot travel full.

- To illustrate this benefit, imagine that the system in Figure (a) is optimal, and that its vehicles leave the depot only 1/2 full. 假设图 a 中的最优配送批量是 1/2 车容量
- In other words, we are assuming that increasing (or decreasing) the delivery lot size is not desirable because holding costs at the destination would then be too large (or too small). 多之则降低配送频率，提高目的地的保管费用；少之则提高配送频率，提高运输费用；
- Furthermore, although one could presumable reduce costs by using delivery routes with two stops without changing the delivery frequency, we also assume that the loading/unloading operation is so slow that there is no time in a work shift to make more than one stop and return to the depot. 同样，某些情况下可通过让车辆每次服务两个顾客，以在不影响配送频率的前提下降低运输成本。为避免该种情况出现，假设装卸货很慢，以至于无法在一次轮班内停靠多于一个顾客并返回到配送中心。
- Thus, without transshipments, the arrangement can be assumed to be optimal. 在不存在转运时，该排班可设为最优。



- Clearly, the introduction of transshipments as in Figure (b) allows matters to be improved, since the terminal allows the routes to be broken into shorter segments. Although deliveries still take place in half filled vehicles, the terminal is supplied by full vehicles. Further improvement is possible. 图 b 中引入的转运可使得长距离的配送被分割为更短的小段。尽管最终的配送仍然由半满的车辆实现，转运站处的需求可以由满载的车辆供给
- Because the deliveries now start from a place closer to the destinations, there may be time to make more than one stop and reduce even more the daily distance traveled for local delivery, as illustrated in Figure (c). No change in delivery lot sizes results 现在最终端的配送的起点距离终点更近，因此最终的本地运输每次可访问多于一个顾客，更进一步降低每日的运输距离。如图 c 所示，此时终端配送的顾客批量没有发生变化

- In summary, terminals allow us to **decouple the line-haul transportation and local delivery operations**, enabling us to use larger vehicles for linehaul than are used for delivery; they also increase the number of delivery stops that can be made without violating route length limitations.
- We will see in N-to-N problems that terminals can also play a “break-bulk” role.

- The structure of a distribution system is defined by the **number and location of the transshipment points**, the **routes and schedules of the transportation vehicles**, and by the **paths and schedules followed by the items**.
- Usually, the number and location of the transshipment points cannot be changed as readily as routes and schedules. The latter are tactical level variables, and the former strategic variables. Since customers are usually not affected by routing changes, the vehicle routes and item paths can often be viewed as operational level variables, which can be changed even more readily than the delivery schedules.

关于枢纽选址的假设

- For long term (strategic) analyses, decisions at all levels (operational, tactical and strategic) need to be made. For this type of problem we will **develop optimal system configurations assuming that the terminals can be opened, closed and relocated without a penalty**.
- This simplification is not as restrictive as it may seem because, if conditions change slowly with time, locations do not need to be changed often. If $\lambda(t, \boldsymbol{x})$[1] changes slowly with time, near-optimal terminal locations will be shown also to change slowly with time (this dependence is even more sluggish than the dependence of headways and number of stops on t) 假设需求函数随着时间和区域的变化不大，则近似最优的枢纽选址随着时间的变化也比较慢；这种缓慢变化的幅度，相比配送频率和每次访问的顾客数的变化更小。

[1] demand per unit time unit area.

选址问题

Because the overall cost is not overly sensitive to the specific locations, one can keep a given set of terminals for a long time before some need to be opened, closed or relocated. In any case, relocation costs are likely to be greatly reduced by current trends in the logistics industry, such as the advent of “third-party logistics” firms that furnish full service terminal/warehousing facilities; 由于最终的成本与特定选址的关系不强，在中转枢纽开放、关闭、移址之前，其存在时间较久。现在物流行业的趋势是移址的费用被大大降低，例如，提供全部中转/仓储服务的第三方物流开始出现。

需求函数的假设

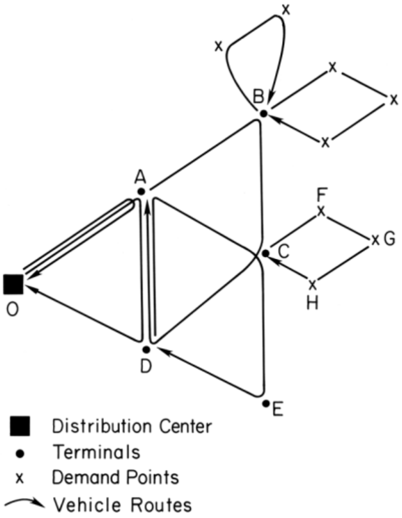
- Unless the changes in $\lambda(t, \boldsymbol{x})$ arise from policy decisions (e.g. expanding the service region over time), the timing of changes to λ may be hard to predict. Without reliable information on them it might be reasonable to design the system as if the changes occurred gradually, using a **smooth forecasted** $\lambda(t, \boldsymbol{x})$ demand density, or else adapting to the **current circumstances as time passes**.
- In either case one would rarely expect the optimal distribution of terminals to change rapidly with time, and it should be possible to design a strategy for opening, closing and relocating terminals that maintains a near-optimal distribution of terminals without large relocating costs.

短期规划

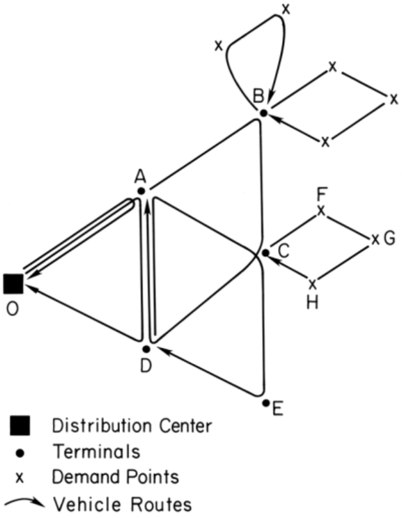
- For the short term one may be interested in adjustments to the tactical and operational decision variables. We may want to determine the best set of **vehicle routes and frequencies for a given set of terminals**; including, of course, the possibility of not using some of the terminals. These (tactical) problems will also be discussed in the talk, although strategic analyses will be its main focus.

- Obviously, the design problem is very complicated if considered with all its details. Our immediate goal, thus, will be to reduce it to a form involving little data and few decision variables, yet capturing the essence of the logistical costs.
- The remainder of this section is devoted to this endeavor; it describes some properties of near-optimal distribution systems with terminals that allow the formulation to be greatly simplified.

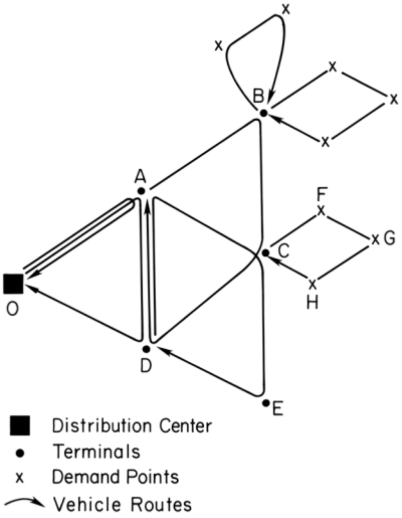
配送系统示意图



- The figure depicts a physical distribution network to carry items from one depot to multiple customers. The network includes terminals (dots on the figure), and multi-stop vehicle routes (looping arrows) that may stop at terminals and customers (***x***'s).



- Because we are only looking at distribution, we shall assume that a vehicle only loads items at the beginning of its route and only distributes them in succeeding stops. This is a reasonable assumption because the within-vehicle sorting complexity and stowage/restowage costs would increase substantially otherwise during a tour. Even collection/distribution systems, for which the savings of interspersing pick-ups and deliveries are obvious, tend to segregate them on individual tours.



- An item that needs to be taken to destination F in figure may use vehicle routes (OAO, ABCDA, and CFGHC), or (OADO, DACED, and CFGHC) to get there. In the first case, it would use path OABCF and in the second case OAD-ACF. If redundant network structures, where some destinations can be reached by more than one path (such as those of the figure), can be shown not to be necessary, we would like to rule them out before starting any analysis. This is done next.

Near-optimality of non-redundant networks

Here we show that, in many situations, networks providing redundant paths are not needed because total cost is concave on flow.

Near-optimality of non-redundant networks

- For the proof we focus on an operational problem, where the terminal locations, vehicle routes and schedules are fixed but one can choose the **item paths and vehicle sizes**. Then, the daily cost of transportation will be the sum of the transportation costs on each route.
- Each one of these route costs should only depend on the size of the vehicle used on the route. Furthermore, the relationship should be **concave** and **increasing** because of the economies of scale in vehicle size. Clearly then, on each route we should choose the smallest vehicles able to carry the load.
- Because **the size of the vehicle must be proportional to the flow of items on the first link of its route**, and **these link flows are linear functions of the item path flows**, transportation cost must be a concave function of the path flows. 车辆的规模应该与它路径中第一个路段的流量成比例，而路段的流量是使用该路段的货物路径流量的线性函数，因此运输成本是路径流量的凹函数。

Near-optimality of non-redundant networks

- Assuming that the path of each item is chosen at the distribution center 0, **independently of the time at which it becomes available for shipment** and of **the characteristics of the item**, we see that the average time that items are waiting outside vehicles on a specific path is not affected by the path selection strategy at 0; the average time is fixed.
- Since travel times are also fixed, total inventory costs must be linear in the path flows. Therefore, the total distribution cost (if rent costs are ignored) must be concave in the path flows[2]. (We recognize that rent costs are not concave. These costs, however, are typically small compared with transportation costs and should, thus, be unable to reverse the effects of concavity.)

[2] 配送成本由库存成本和运输成本构成，且凹/凸函数加上一个线性函数不改变凹凸性。

两种例外情形

- Before discussing the implications of concavity, it is worth clarifying the two exceptions that were made in the above argument.
- If **the selection of a path** for an item is allowed to **depend on the time it becomes available for shipment** (e.g., passengers using public transportation systems will often choose the first of several lines to depart, if there is a choice) the stationary inventory cost depends on flow; examples can be built where total inventory cost is convex in the path flows. **Even in the (rare) case where dynamic path selection is an option, it is unlikely that one would provide multiple paths to exploit such dynamics**. 配送时间可选

两种例外情形

- The second exception refers to **items of different characteristics**. As shown in the 1-to-N distribution system without transshipment, sometimes it is advantageous to send items of widely varying prices per unit weight on different paths (e.g., expensive items by air freight and cheap goods by land). 异质货物
- In such cases, the pipeline inventory cost is not linear in the path flow; it depends on which items are sent on specific paths. The cost concavity argument does not hold either.

- If all customers are treated alike — asymmetric strategies where this is not the case will be discussed later — and rent costs are not dominant, then **total costs are concave in the flows**; in other words, there are scale economies.
- In this case, as we showed in the 1-to-1 distribution system, only one path should be used to reach each destination.

- These arguments also apply if the destination is an intermediate terminal because intermediate path flows are linear functions of path flows and concavity is preserved. Consequently, path redundancy to either intermediate or final destinations is not needed.
- If follows that each terminal, or final destination point, needs to be served by **only one vehicle route**. Otherwise, the stop could be bypassed by all vehicle routes carrying no flow to it for a reduction in transportation cost.

- This implies that **each destination point should be on only one route from only one terminal**. That is, if we define the level-n influence area of a terminal as the set of points that are served from it with n or less transshipments at succeeding terminals, level 0 influence areas must form a partition of the service area. 一个中转枢纽的第 n 级影响区域为从它出发需要 n 次或者更少转运次数到达的点集。第 0 级影响区域构成其服务区域的一个分割。
- Since each terminal can only be on one vehicle route starting at another terminal, the influence areas at every level must also form a partition. 由于每个中转枢纽仅位于另一个其他中转枢纽的路径上，每级影响区域都构成一个分割。

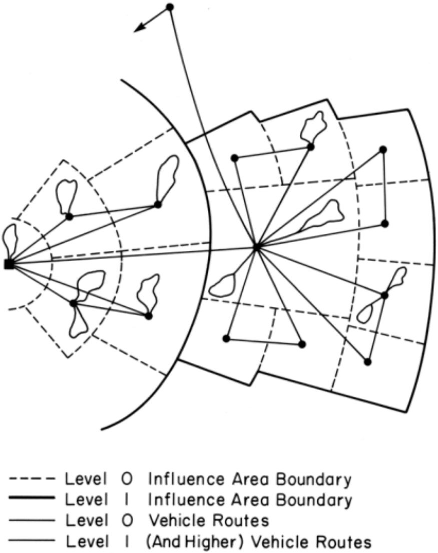


Figure: A possible structure where influence areas are simply connected sets (with no holes). We will reasonably assume from now on that influence areas are simply connected.

Near-optimal operations

- Given the dispatching frequency from every terminal, we describe here which stops should be served from which terminals, and the structure of the vehicle routes based at each terminal.
- To build such routes in a near-optimal way for a given set of stops their length should be minimized. Otherwise, a reduction in length could reduce total cost through decreases in the pipeline inventory cost, and the transportation cost. Thus, it seems logical to construct the routes with a VRP technique

Near-optimal operations

- We also need to decide which stops are to be served from which terminal. It will be assumed that vehicle routes do not stop at both terminal and final destinations.
- This is reasonable (and common practice) because otherwise **sorting and scheduling work would increase substantially in size and complexity**.
- For systems with more than one level of terminals it will be assumed that vehicle routes only stop at one level of terminal. This is also reasonable because substantially different flows pass through terminals at different levels, and it just doesn't seem economical to serve them equally frequently with the same tour.
- Thus, the routes from any level-j terminal[3] will be assumed to serve all the level-$(j-1)$ terminals in the level-j influence area, or the customers if $j=0$.

[3]We say that a terminal is of level$-j$ if its items are transshipped a maximum of j times after passing through the terminal. The terminal serves a level$-j$ influence area.

Near-optimal operations

- As a result, a set of influence areas and terminals (at all levels) defines the stops served from every terminal. Since the VRP solution defines the routes, the overall strategy is defined by a set of **influence areas** and a set of **dispatching frequencies**

Near-optimal operations

- Because level-$(n-1)$ influence areas are usually contained in much bigger level-n influence areas (otherwise terminals would not be cost-effective), the flow through a terminal usually is considerably smaller than the flow through the terminal feeding it.
- This, among other reasons such as restrictions to heavy vehicle travel on local streets, makes it economical to distribute items in loads smaller than those used to feed the terminal. Thus, **each item-mile requires more vehicle-miles during distribution from the terminal than while being fed to the terminal**.
- Consequently, in order to minimize vehicle-miles of travel, terminals should be centrally located within their influence areas. This is true for influence areas of all shapes.

Near-optimal operations

- The same location principle was applied to the one-dimensional terminal location problem. Although the optimal terminal locations obtained in the one-dimensional problem were not exactly in the center of each interval, the displacements were slight.
- Not surprisingly, the CA approximation with centered terminals was found to be quite accurate. A two-dimensional analysis confirms that this simplification leads to negligible errors.

- Unlike VRP zones, influence areas should not be elongated toward the depot; their shape should be selected to be **as close to a circle centered around its terminal as possible**, because this minimizes vehicle-miles.
- Of course, perfect circles cannot be used because they would not fill the space, but non-elongated shapes — "round" we call them — that approximate circles (e.g. squares, hexagons, and triangles) should be appropriate. The specific round shape used does not matter much

- It is thus possible to describe a near optimal system structure by **the sizes of the various level influence areas**, $I_j(\boldsymbol{x})$, as a function of position — together with the **dispatching headways** used at each level.
- As stated earlier, this reduces the very complex design problem to the determination of just a few decision variables.
- Building on this result, the following sections show how to estimate cost and develop a system design for various scenarios.

Any questions?

Readings

- Daganzo. Logistics System Analysis. Ch.5. Page 161-170.