The Design of a New Freight Distribution System in Venice[1]

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Abstract

This paper examines the reorganization of freight transportation in the city of Venice, Italy. Most of the freight arrives from the mainland by trucks, but must be carried to the final customers by boats, through a network of small canals. The existence of constraints, related to the widths and clearances of the canals, makes it necessary to use boats of different sizes and capacities. In this paper, we analyze the transshipment operations from trucks to boats, and the organization of the boat distribution.

Currently, the lack of an adequate terminal facility prevents items offloaded from land vehicles from being stored and sorted prior to being loaded on boats. As a result, items are transshipped directly from trucks to boats. This form of operation generates delays for the vehicles, resulting in very long queues, and inefficient boat shipments. Consequently, dispatched boats are insufficiently loaded with deliveries to be scattered throughout the city, creating an inefficient use of different vehicle types.

A new system is deemed necessary by the players involved (i.e., the local government, and the boat carriers), especially because a more fluid and controlled traffic flow would have a positive impact on the ecology of this unique city. Recently, the boat carrier organization proposed to the local government a new transshipment terminal with a warehouse. This paper evaluates how such a terminal would be operated, so as to take maximum advantage of the newly available sorting and storage capabilities due to the warehouse facilities.

The strategy that we developed would enable a more efficient use of different boats, consistent with the introduction of the new terminal. Similarly, the paper estimates the benefits of this new form of operation, using simple analytical formulae and continuous approximations, in lieu of detailed optimization methods.

Introduction

The role of distribution logistics, as a strategic factor for competitive advantage in many different business areas, is validated by the numerous research studies; see, for example, the cited literature in Daganzo (1996) and Federgruen and Simchi-Levi (1995).

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Sometimes issues other than costs and product quality come into play, such as the environmental impact on a specific territory. These new factors make the problem much more complex, though admittedly more stimulating as well, both for the theoretical relevance of the problem itself and for the larger impact that it may have on the community.

In section 1, the distribution problem in Venice is described, and a special focus is given to the city's unique characteristics that are involved with the logistic system. In section 2, the scope of the present research is defined, along with the main factors affecting the logistic system. In section 3, various scenarios for the transshipment schemes are evaluated. In section 4 the boat distribution problem is addressed.

1. Problem Description

1.1 Special Features of the City

Venice has many features that make it different from any other city. A small archipelago of approximately 120 little islands, it is located in the middle of a lagoon, about two miles from the mainland and one mile from the Adriatic Sea. These islands lie on an elaborate network of 177 canals, most of which are very narrow. A large number of small bridges link most of the islands, and a long bridge connects Venice with the mainland.

The traditional transportation media (i.e., cars, trucks, trains) can reach the terminus of this bridge, on the city side, but such vehicles cannot get within Venice, as travel through Venice necessitates a boat, which is the main medium of transportation in the city.

In recent years, it has become increasingly important to safeguard the many monuments and ancient palaces of this historical city. The motorboat traffic is one of the main culprit of the infrastructure deterioration because it creates waves and vibrations in the water. The political orientation of the local government is therefore leaning towards a stricter control of boat traffic. Thus, there is a strong need for a thorough reorganization of the whole transportation system.

1.2 Current Organization of the Freight Distribution

Despite its small size, Venice has a high density of shops, restaurants, bars, hotels, and other public places, all of which require a continuous supplying of goods. Distribution service to these businesses is currently provided by a large number of small entrepreneurs. Having so many businesses entering the area creates a unique challenge: distribution service must be highly organized and well planned. However, small firms don't have boats of varying types and dimensions, which would assure the needed flexibility conducive to efficient organization. Furthermore, there are specific factors that increase the complexity of planning in this very special environment. Because there are different canal sizes, some boats can pass through certain canals only, either because of the narrow width or of some short bridges.

As stated previously, freight is carried to Venice mostly by trucks and it is then transferred to boats. The point at which most of this activity takes place is a dock on Tronchetto Island, a large port zone very close to the terminus of the bridge that links the city with the mainland. An analysis of the flow of freight through the dock, conducted in 1979, shows that in a workweek 650 trucks arrived at the dock, as well as approximately 500 boats. It is reasonable to assume that the flow has been approximately invariant, or slightly increased since then. The highest intensity occurred on Thursday, with a total of 150 trucks. In general, it is possible that a truck splits its load to different boats, or that one boat carries items from different trucks. However, it is necessary that there be a simultaneous presence of boats and corresponding trucks during the handling operations, and that these operations be mostly manual, and, lastly, that there be at least three or four workers per load. There is a peak-time of the early morning, approximately from 6 a.m. to 9 a.m., during which the congestion at the dock is particularly heavy. The idle waiting time for trucks is quite high: 37% of the trucks must wait an average of 30 to 60 minutes, and part of the burden is shared also by boats. Very often boats have to arrive well in advance of the morning in order to find a place on the undersized dock. The logic followed is a kind of "first in, first out," with regard to the place at the dock. What can also happen is that not all the boats that are going to carry one truckload are simultaneously present in the dock, thereby causing the truck to have to wait longer.

Once the loading is finished, the boats go to the final destination; however, in many cases they are only partially loaded. The route is decided at the moment of the departure, relying upon the experience of the boatman. At the final destination, similar problems may occur, due to a limited number of available landing-places in the different zones. Thus, further bottlenecks are sometimes created.

Finally, it is usually necessary to cover the final part of the route by foot, handling manual carts. This last part of the distribution service is sometimes awkward and time consuming, because the carts need to be carried through bridges or narrow and crowded alleys.

2. Research Scope

One can easily see how the redesign of the distribution system in Venice is both a project of large scope and long term. As a first approach, this paper is concerned with models that allow the evaluation of strategic decisions. In addition, some elements of the current research, relevant to the definition of operative procedures, are presented in the final section.

The basic idea is to analyze the costs related to the distribution system at a strategic level, in order to highlight the main trade-offs involved. The focus of the analysis is how to organize transshipment operations in such a way so as to have an efficient distribution in the final phase, from the transshipment point to the final customers. The organization of the truck distribution is out of the scope of this research; how trucks get to Venice is irrelevant to the question that the city has presented.

2.1 Crucial Points

The various players involved with the distribution service recognize that the crucial issues in this logistic system are:

- the congestion at the transshipment point
- the distance traveled by the boats.

Therefore, the following subsections explore these two points.

2.1.1 Congestion

During the peak-hour, it may happen (and it currently does) that long queues of both trucks and boats are generated at the transshipment point. This congestion generates costly delays. The truck delay depends on some aspects of the system configuration which are subject to strategic level decision. This will be explained below. On the other hand, boat delays will probably remain, for the most part, substantially unchanged, given the characteristics of the proposed solution, which would still require that the boats be ready on demand. Therefore, only the congestion reduction benefits related to trucks is taken into consideration in our study.

Currently, trucks directly tranship their loads to one or more boats. Most of them, supposedly, have a pre-determined arrival time. However, especially during the morning rush hour, trucks may find all the available dock space occupied, and have to wait, sometimes for a long time.

Clearly, a facility, such as a warehouse, or a shed, which decouples the trucks from the corresponding boats, can prevent the congestion at the dock. In this way, the trucks can leave immediately after unloading, without delay. As a first approximation, in order to size up such a facility, it will be assumed that the time-dependent flow of freight at the facility is the same as the existing one.

2.1.2 Boat Distance

The boat distance traveled is likely the most crucial point, not only because of the overall efficiency of the logistic system but also for the preservation of the infrastructure. It is a widely accepted fact that in order to reduce the combined boat distance traveled, it is necessary to partition the city into delivery zones. We know that the distance decreases with respect to the square root of the number of zones. (See, for example, Daganzo, 1996.)

For the partition to be feasible, two possible alternatives seem appropriate. The first alternative entail a shed arrangement in which the dock would be divided into areas, each one corresponding to one delivery zone. Each area could include one or more berths, but only boats going to the corresponding zone would moor there. The trucks would stop at all of the areas corresponding to zones where their truckloads are directed. Such multiple-stops at the dock would mean increased unloading costs, due the necessary sorting of the truckloads. Furthermore, there would be costs related to the gathering of information about the final destination of the different items in the trucks.

The second possible alternative entails the use of a warehouse, which would allow trucks to make single stops while consolidating the freight. The use of a warehouse would prevent the trucks from having to stop and unload at many areas, but would introduce a step, which would obviously incur more costs. In fact, this step would introduce a larger facility cost, as well as other costs related to the double handling and internal transfer.

3. Basic Transshipment Schemes

We have identified three basic schemes, or scenarios, for the transshipment operations, which would allow the city to be partitioned into zones. The schemes are: (1) direct transshipment system, (2) shed system, and (3) warehouse system. In this analysis, both the synchronicity of the transshipment and the partition in zones are taken into account. Each scenario is analytically evaluated by means of a cost function that is optimized with respect to the number of zones (i.e., the average zone size) best suited for the particular scenario.

3.1 Direct Transshipment

The first scheme is the simplest possible modification of the way things are currently organized. Such a scheme basically consists of transshipping the freight directly from trucks to boats, by organizing the dock per zone. Figure 1 depicts this first scheme: the dock is divided into as many areas as the desired number of zones. Each boat lands only at the area corresponding to its delivery zone, whereas each truck has to stop at all the zones corresponding to each area to which its load is directed. In this way, it would be possible to partition the city into delivery zones, without using expensive facilities. On the other hand, not only does the problem of the truck congestion still exist, but also the freight on the trucks has to be sorted in such a way that it can be easily unloaded at the different stops.

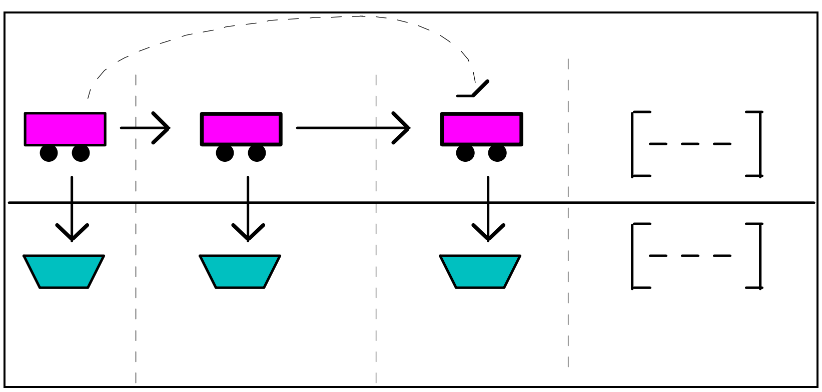

Figure 1

This scenario can be analytically formulated by means of a function, expressing the total cost of the distance traveled by the boats and the transshipment operations. It is assumed throughout this paper that the time unit to which the cost function is referred is the day; hence, the measure unit of the cost function is $ per day. In this analysis, both the costs of the truck transportation and of the final handcart delivery are not included, as it is assumed that the reorganization would not appreciably change these costs. The cost function has the following form:

$$c_{bd} \cdot \left(\bar{d} + \frac{k}{N^{1/2}} \right) \cdot \frac{q}{s_b} + c_w + c_{ms} \cdot N \ \$/day.$$

The number of zones N is the only decision variable; the other components are parameters of the problem:

- c_{bd} is the boat cost per unit-distance;
- c_{ms} is the multiple-stop cost per day;
- c_w is the combined truck-waiting cost per day;
- $\bar{d}$ is the average line-haul distance traveled per boatload;
- k is the factor that expresses the local distance;
- q is the amount of freight delivered in weight unit-freight in tons per day;
- s_b is the capacity of the boat in tons.

The first addend represents the combined distance traveled by the boats in a day, and it has two components: the line-haul distance from the transshipment point to the delivery zones, and the local distance traveled within the zones. If the distribution area is divided in nonoverlapping zones, the line-haul distance is optimized by following the shortest path from the transshipment point to the zone. The lower-bound of the line-haul distance is reached when all full boatloads are dispatched.

The local component instead decreases with the number of zones N, for the average zone size is inversely proportional to N. Daganzo (1996) indicates that the local distance decreases with the square root of the number of zones, with a given proportionality coefficient k. To obtain the combined distance, the average distance is multiplied by the number of boatloads per day, given by the ratio $\frac{q}{s_b}$. Here it is considered a fixed boat size s_b. Section 4 deals with the issue of different boat capacities.

The second addend is the truck waiting cost. This cost depends on the truck arrival and boat departure patterns, and in this scheme, it remains unchanged respect to the current situation. An example is given in Figure 2, which represents a plot of the cumulative amount of freight that arrives to the dock by truck (curve A), and leaves by boat (curve D), over a hypothetical workday. The area between the two curves represents the total wait time, in tons per hour. The truck waiting cost is proportional to this area: dividing it by the average size of a truck shipment yields the waiting truck-hours.

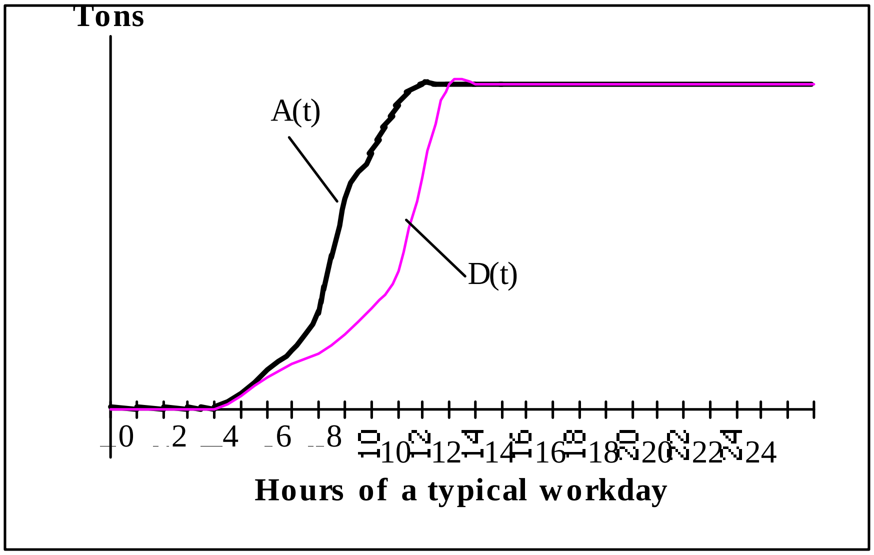

Figure 2

The third and last addend is a cost which can be referred to as "loading effort." This addend captures all the cost components related to the dock partition: information, sorting, and multiple stops, as delineated above. The "loading effort" is based on the assumption that the number of actual stops for the average truck is proportional to the number of zones.

In this scheme, it is also possible to adopt an alternative way of distributing the freight among the different areas on the dock. For example, one can use some kind of conveyor to transfer the freight, in such a way so as to allow the truck to stop only once to unload the whole load. Conceptually, there is no difference in the cost function structure: either way, there is a cost component that increases with the number of zones.

The trade-off on the number of zones is evident: the boat distance cost decreases, and the loading effort cost increases as the number of zones increases. Because of space constraints, the number of zones is rather limited. The only currently available dock does not allow more than approximately ten zones.

In this scenario, the optimal number of zones can be obtained by solving the following constrained economic order quantity (EOQ) problem:

$$\min\left\{c_{bd}\cdot\left(\bar{d}+\frac{k}{N^{1/2}}\right)\cdot\frac{q}{s_b}+c_w+c_{ms}\cdot N\right\},$$
$$\text{s.t.}$$
$$1\le N\le N_{\max}$$
$$N \text{ integer}$$

where $N_{\max}$ is the maximum number of zones.

3.2 System of Sheds

The second basic scheme is similar but includes a rapid way of unloading the trucks and small storage buffers for each destination zone. This scheme prevents the truck congestion and allows an asynchronous transshipment, as depicted in Figure 3.

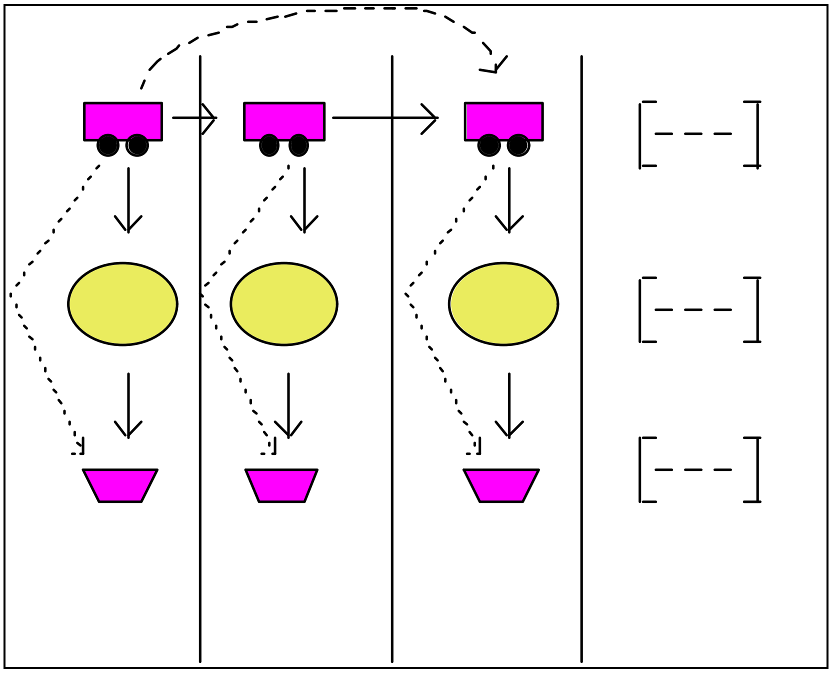

Figure 3

The cost function that captures the elements of this scenario is similar to that of the previous scheme. Essentially, the truck congestion cost is now replaced by the cost of operating the sheds. The trade-off in the decision variable *N* remains unchanged.

The expression (still in units of $/day) is:

$$c_{bd} \cdot \left(\bar{d} + \frac{k}{N^{1/2}} \right) \cdot \frac{q}{s_b} + c_{ms} \cdot N + c_{sh} \cdot q_{sh} \ \$/day,$$

where:

- c_{sh} is the handling cost per unit freight, and
- q_{sh} is the amount of freight that actually passes through the sheds per day.

The first two terms represent the cost for the boat distance and the multiple stops. These components are the same as those costs in the first case. The third term represents the extra unloading cost, plus a facility rent cost. Note that the rent is modeled, for the sake of simplicity, as being proportional to the amount of freight actually handled. This modeling is logical since the size of the facilities should roughly be proportional to this flow. Moreover, even if the facilities were owned by the city, one could compute an equivalent rent, based on the amortized investment cost, which should still be roughly proportional to the amount of freight handled.

In this way, the cost is made proportional to the amount of freight that is actually handled. This maximum accumulation in the sheds does not depend on the decision variable *N*, but rather on the freight arrival and departure patterns, which are exogenous data. In the example given in Figure 4, the curve *A(t)* represents the freight arrival, and *D(t)*, the departure by boat, on a typical workday. The area between *A(t)* and *D(t)* is the same as the area in the previous case; however, now it represents the freight delay only, not the truck plus freight delay. The trucks, in fact, unload and leave as soon as they arrive; the physical unloading time is fixed and therefore neglected in the analysis. The freight delay is not considered a cost component, since it does not change from the previous scenario and, in any case, is much smaller than any other component of the objective function.

It is reasonable to assume that one ships through the sheds the minimum possible amount of freight q_{sh}, in order to minimize the handling costs. This amount is minimized by adopting a LIFO scheme: if a truck arrives and there is an available boat, the truck immediately unloads onto the boat, even if there is some freight waiting in the shed.

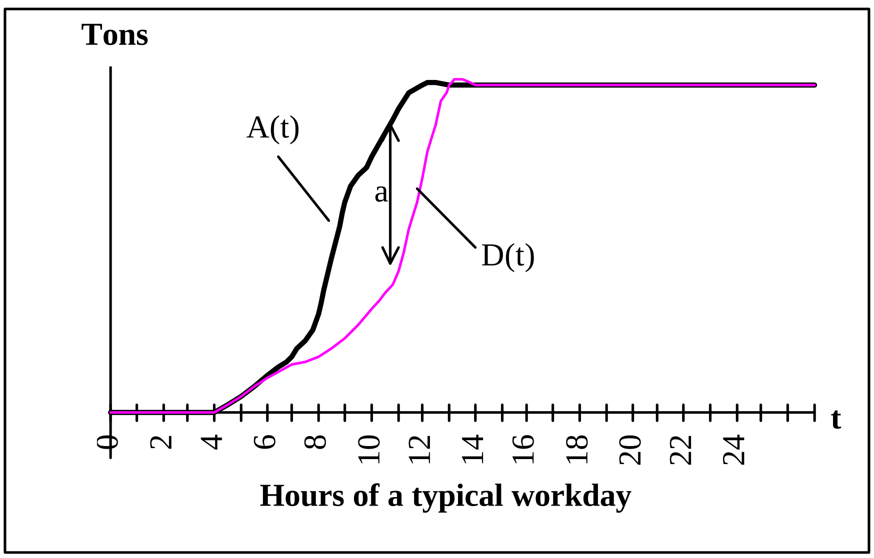

Figure 4

For typical patterns, such as the ones in the picture (which fit the Venice case) the vertical separation *a* also gives the total amount of freight handled, q_{sh}, with a LIFO rule. This fact justifies the amalgamation of the rent cost and the handling cost into a single term.

As in the previous case, the optimal number of zones can be obtained by solving the following EOQ problem:

$$
\begin{aligned}
&\min\left\{c_{bd}\cdot\left(\bar{d}+\frac{k}{N^{1/2}}\right)\cdot\frac{q}{s_b}+c_{ms}\cdot N+c_{sh}\cdot q_{sh}\right\},\\
&\text{s.t.}\\
&1\leq N\leq N_{\max}\\
&N\ \text{integer}.
\end{aligned}
$$

Clearly, the shed system will be "better" only if $c_{sh}q_{sh} < c_w$. These two costs, however, are borne by different players, so that, ultimately, the decision has to be a political one.

3.3 Warehouse

The third basic transshipment scheme consists of using a warehouse to sort and store freight. In effect, the warehouse would carry out the dual purpose of partitioning the city in delivery zones, and thereby preventing congestion.

Under this scheme, most of the freight has to necessarily pass through the warehouse, in order to be sorted. Only the rare truckloads that are directed to one zone can be directly transshipped to the boats. As a consequence, the handling cost is higher than the cost of the shed system. In addition, this plan requires a larger amount of capital, and a consequent amortized rate. On the other hand, such a system allows the partition of the city into a higher number of zones than was the case in the first two schemes. Figure 5 depicts this third scheme.

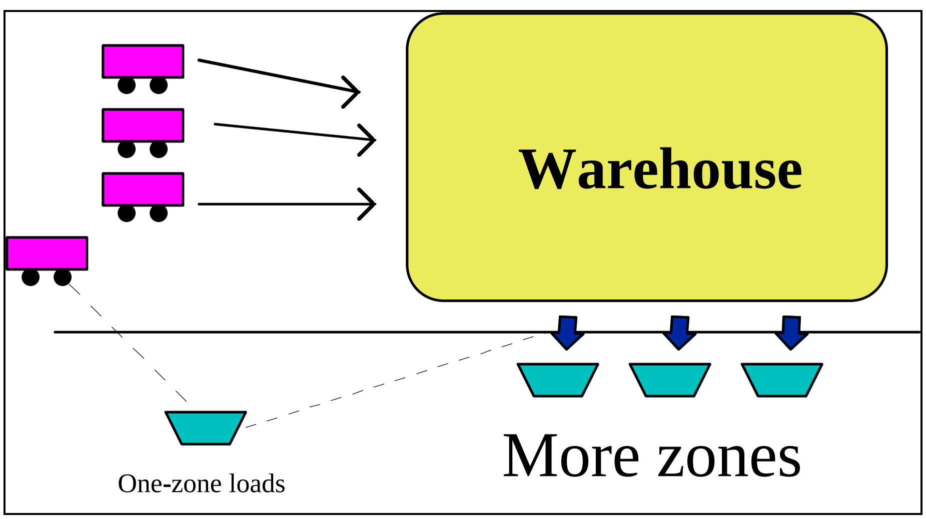

Figure 5

The arrival and departure patterns are now different, as one can see in Figure 6. The boat departure rate will be higher, since it is expected that this plan will provide a more efficient loading system; nevertheless, the boat departure is delayed. In the case in which a system of sheds is employed, it is reasonable to assume that the boat departure is not delayed because the freight passes through the shed only when a boat is currently being loaded, and the number of zones is the same as it is in the direct transshipment. In the case of the warehouse, however, some delay is unavoidable. This is a result of having a more complex sorting requirements and needing to accumulate more freight (for an increased number of zones) before delivering the freight in full boats. However, the freight delay is not considered a significant cost component.

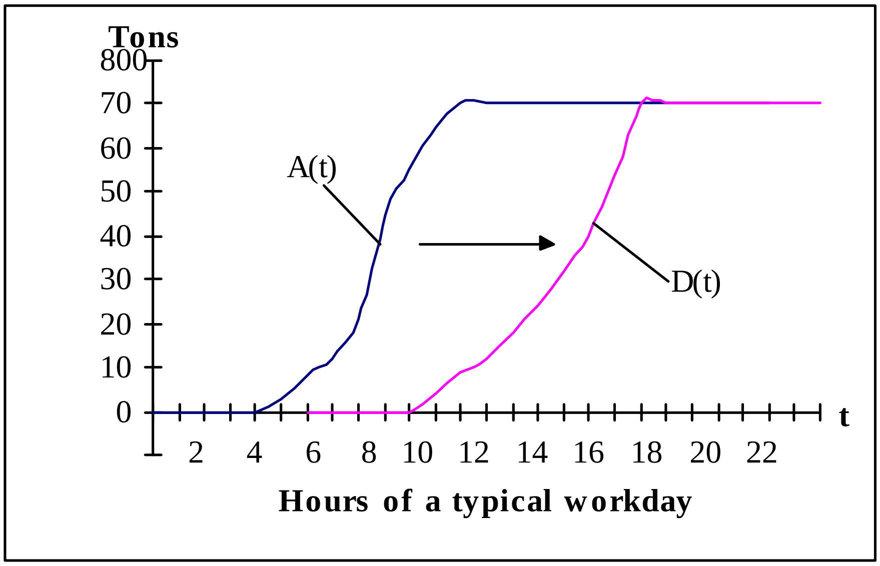

Figure 6

The cost function is as follows:

$$c_{bd} \cdot \left(\bar{d} + \frac{k}{N^{1/2}} \right) \cdot \frac{q}{s_b} + c_r \cdot q_{wh} + c_{it} \cdot q_{wh} \cdot N \ \ \$/day,$$

where

- c_r is the rent and handling cost per day per unit-freight;
- c_{it} is the internal transfer cost per day per unit-freight;
- q_{sh} is the amount of freight passing through the warehouse.

The first component has the same boat-distance as the cost in the previous cases. The second component is the facility rent cost (higher than the cost for the sheds) plus the cost of loading and unloading the items, without physically transport them. The third component is the cost of the internal transfer of the freight within the warehouse. This cost is weighted in such a way to be proportional to the number of zones. Insofar as the delay of the items, it should be roughly proportional to *N*, and, if desired, one could include the extra cost of delay by slightly increasing c_{it}.

Using such a facility allows us to partition the city into more zones: the same berth of the warehouse can be used for boats going to different zones. Again, the optimal number of zones can be found by solving a simple *EOQ* problem:

$$\min\left\{c_{bd}\cdot\left(\bar{d}+\frac{k}{N^{1/2}}\right)\cdot\frac{q}{s_b}+c_r\cdot q_{wh}+c_{it}\cdot q_{wh}\cdot N\right\},$$

$$\text{s.t.:}\quad N\le N'_{\max}$$

$$N\ \text{integer},$$

where $N'_{\max}$ is the maximum number of possible zones in the warehouse option, and where $N'_{\max} > N_{\max}$.

3.4 Comparison

The cost functions depend on a set of parameters; unfortunately, at the time of our research it was not possible to have an accurate estimation of these parameters. A set of surveys in the field pointed out that it is quite difficult to get a sensible estimate of the parameters. The difficulty is due to the fact that different players involved in the distribution system have their own points of view. For example, the local government gives top priority to the preservation of infrastructure, (i.e., minimization of the distance traveled by the boats), which is less important in the eyes of the boatmen. What appears clear is that it is appropriate to give considerable weight both to the boat distance and to the multiple stops made by the trucks. The importance of the boat distance has been explained previously, and the multiple stop operations are considered extremely awkward, not just by the truck operators but also by the boat crews (the boat crews are in charge of the operations, along with the truck drivers).

A sensitivity analysis of the values of the parameters reveals the following. As a general consideration, we found that in the case of the direct transshipment and the system of sheds, the cost starts to increase very quickly with the number of zones. The optimal number of zones is always quite low; even with very little weight assigned to the multiple stop cost, and with considerable weight assigned to the boat distance the number of zones never gets above 6 or 7. The warehouse cost, instead, always decreases with the number of zones; the boat distance component dominates the cost of internal transfer. The optimal number of zones is therefore equal to the upper limit. Figure 7 depicts a case with a sensible choice of the parameters.

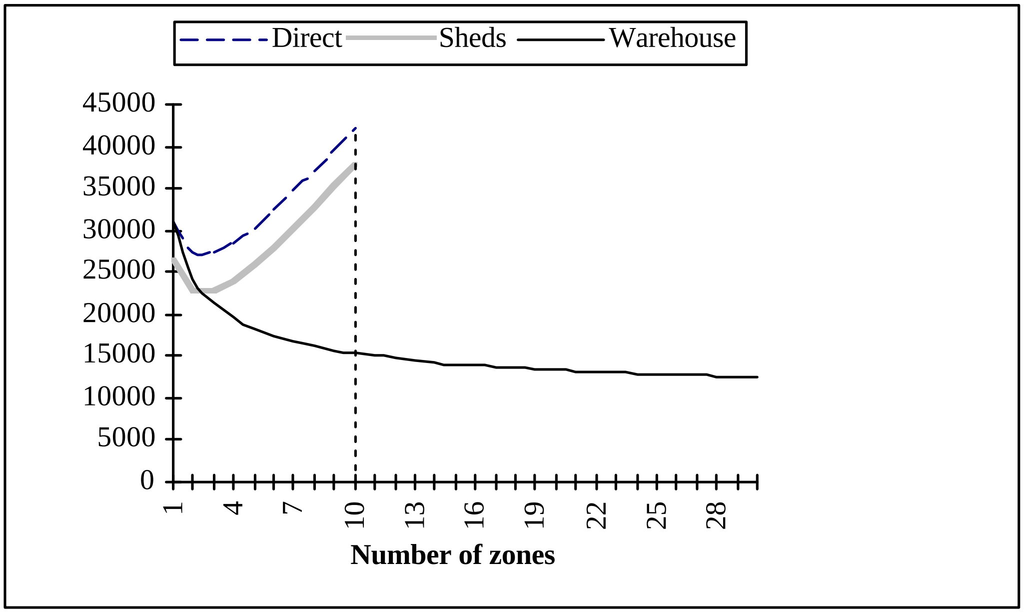

Figure 7

The upper limit N'_{max}, which has been set to 30, depends on two factors. The first is the handling within the warehouse. The second is the requirement of sending full boats, which suggests that the number of zones should be several times (i.e., 5 times) smaller than the number of boatloads shipped per day, which, in this case, is 150. Thus, each zone would receive, on average, at least several boatloads. See section 4.

The figure is not qualitatively different for other choices of the parameters. The sensitivity analysis points out that the best option is the warehouse, for most parameter sets. This holds true especially when considerable weight is assigned to the boat distance, which is a very realistic hypothesis. Options other than the warehouse would be preferred only for an unreasonably high rent cost. In conclusion, we believe that the most suitable scenario for the transshipment operations consists of the use of the warehouse and the partitioning of the city into approximately 30 zones.

4. Boat distribution

This section examines the boat distribution question in further detail, assuming that the warehouse is the adopted transshipment scheme. Two main issues are addressed: the boat-zone assignment (section 4.1), and the stop frequency and location within a zone (section 4.2). The main focus is the assignment of zones to different boats. The precise routes followed by the boats are not of issue, drivers will choose the "best" path, based on their experience.

4.1 Boat-zone assignment

In this section, two basic factors are analyzed: the total boat distance (line-haul and local distance) and the final delivery organization. As explained previously, it is necessary to carry freight by handcart, from the boat stop to the final destinations. This "cart distance" or “walking distance” is a factor that has not been dealt with explicitly in the previous analysis because this factor was not directly affect transshipment operations or boat-miles. This part of the distribution process, however, is also costly and time-consuming, as carts often have to pass through awkward bridges and narrow lanes.

The local distance traveled by both boats and carts is minimized by the highest feasible number of zones. Thus, the proposed optimum, outlined in the previous section, would continue to be optimal for a more complex model in which "cart-miles" had been explicitly incorporated into the objective function.

Next, we explore how to organize the distribution in such a way that it will reduce the line-haul distance, while keeping the local distance low. The trade-off between boat stopping time and walking distance is explored, as well as the complicating implications of the existence of different boat types. Two basic guidelines are proposed to minimize the line-haul distance:

- the boats have to be filled to capacity;
- the delivery zones cannot be overlapping.

The rationale for filling the boats to capacity, as well as the necessity of defining non overlapping zones, is intuitive; the goal is to avoid duplications of line-haul portion of the boat trips. This may be difficult to do in a real-life situation, given daily demand fluctuations; nevertheless, operating plans can be designed for accomplishing the goal approximately.

We proposed earlier that the number of zones needs to be limited, (N'_{max} = 30), in order to allow the demand for each zone to be high enough to dispatch a consistent number of full boatloads. Consequently, the load splitting between zones is reduced and the operating plans are made simpler. Moreover, relatively big zones enable easier handling operations which means that a boatload can be dispatched sooner, thereby reducing the delay indicated in Figure 6.

Also, the system organization is influenced by the different sizes of the canals and boats. In this paper, we will refer to two size categories: "big" and "small" boats and canals. The situation is, in reality, more complex but our dichotomy should suffice to illustrate the issues.

Moreover, we will assume that most of the boats make only one trip per day, and that boat distance can be saved by using the larger capacity boats to serve remote locations. If the fleet composition is a decision variable, the best solution would be to use only big boats. This solution is not acceptable, however, because only a few canals are accessible to big boats and using only big boats would thus imply a very high walking distance.

In order to obtain some qualitative conclusions that may apply to locations other than Venice (e.g., for land transportation problems with small streets), the boat-zone assignment is investigated in a very simple geometry.

This geometry may be represented by an infinite rectangle of big canals in which the distance is given by the L_1 metric (see Figure 8). The big canals are located at a given distance from each other, and an infinitely dense grid of small canals covers the space between these big canals. It is as if the small canals could reach any point. The big boats can go through the big canals only, the small ones, through all of them. The big boats have a lower transportation cost per item, but since they have to stay in the big canals, it becomes necessary to cover some walking distance. The small boats have a higher transportation cost, but they can arrive everywhere. Hence, the trade-off is between the cost of the walking distance and the higher transportation cost per item, which characterizes the small boats.

The problem can be conceptualized as follows: where do we send the big boats, given the routing constraints? With the simplified geometry adopted, the problem is to determine the width of the area around the big canals, which is to be covered by big boats. (Hereafter, we will call this area "swath."). This width gives the transversal walking distance for the freight delivered by big boats. There are two different scenarios in which the problem can be faced: the fleet is a decision variable (a long-term problem) or the fleet is fixed (a short-term problem).

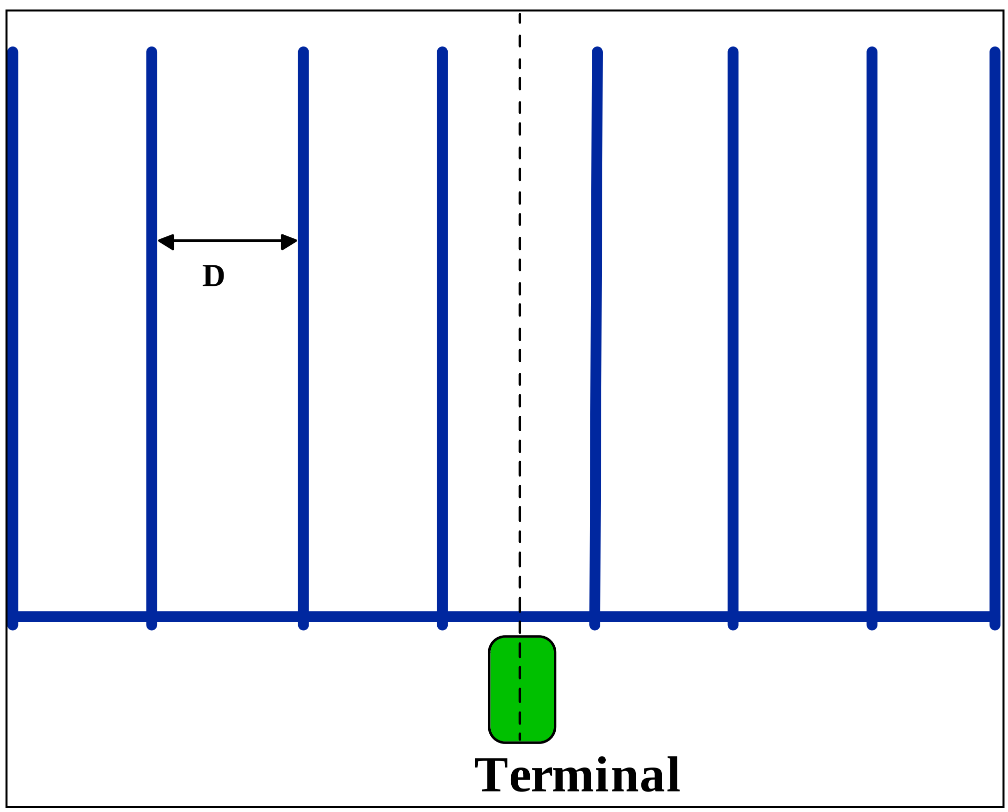

Figure 8

4.1.1 Flexible Fleet

Clearly, the swath width *s* depends on the distance from the transshipment point, *x*: $s = s(x)$. The farther the boat goes from the terminal, the greater the savings, due to the use of a big boat. As a consequence, we can justify having a larger swath width. The aim is that, at the boundary of the swath, the various costs of delivering one unit of freight with the different boat types must be equal. This marginal cost optimality condition is given by the following equation:

$$c_{Ls}x + c_{ss}s(x) = c_{Lb}x + c_{wk}s(x),$$

where

- c_{Lb} is the cost per unit-distance traveled by one big boat;
- c_{Ls} is the cost per unit-distance traveled by one small boat in a big canal;
- c_{ss} is the cost per unit-distance traveled by one small boat in a small canal;
- c_{wk} is the cost per unit-distance traveled by a cart along the swath width.

The left-hand side of the equation is the cost for delivering one unit of freight by a big boat, given by the cost of the "line-haul" distance *x* plus the cost of walking the swath width. The right-hand side is the cost of delivering one unit of freight to the same point by a small boat. It is assumed that there are separate transportation costs in the different canals for the small boats.

From this equation we immediately derive a closed-form expression for the optimal width *s(x)*

$$s(x) = \left[(c_{Ls} - c_{Lb}) / (c_w - c_{ss})\right] \; x \le D/2,$$

where *D* is the distance between big canals.

The swath width is 0 with x=0, and it increases linearly with the distance from the terminal, up to the value x_{crit} such that $s(x_{crit}) = D/2$. Beyond x_{crit}, the swath with is *D/2*, and all the distribution would have to be done by big boats. This information can be used to determine the total area of the city that will be served by small boats[2] and their respective demand in slot areas. Therefore, one could decide the necessary number of boats of each type.

A similar approach. and one that would be easier to implement, involves choosing $\tilde{x} = \dfrac{x_{crit}}{2}$, and then using large boats only above this distance.

4.1.2 Given Fleet

In this case, we would simply look for the value of $\tilde{x}'$, as close to $\tilde{x}$ as possible, so that the demand from the city region, with $x > \tilde{x}$ ($x > \tilde{x}$), can be met with the available boats.

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[2] For our simple geometry, the area covered by small boats is given by $\int_0^{D/2} 2(kx)x\,dx = 1 - \dfrac{D^3}{12k^2}$, where k is the slope $\left[(c_{Ls} - c_{Lb}) / (c_w - c_{ss})\right]$.

4.2 Number of Stops per Boat Trip

Once the partition is determined, the next step is deciding how often, and possibly where, the boats have to stop. Although these decisions will be delegated to the boatmen, an understanding of the trade-offs they face might be useful, if a more detailed cost assessment is later required as part of the negotiation.

An interesting approach, based on the minimization of the total time consumption, is described in Ieda et al. (1992); this model deals with freight pickup and delivery in the Tokyo metropolitan area. The model presented in this paper has been adapted to the Venice case, and is based on the trade-off between number of stops and walking distance. Each stop implies maneuvers that are often awkward and time-consuming; therefore, one of the goals of the boatmen is to minimize the number of stops. On the other hand, the fewer stops that a boat makes the longer the combined distance to be covered by handcart.

The total time spent during a boat tour that follows a given route can be expressed as follows:

$$\frac{D}{V} + t_1 C + t_2 N_{stop} + \frac{1}{2}\frac{t_3}{N_{stop}} \text{ hours,}$$

where

- C = boat capacity, in tons;
- D = tour distance, in miles;
- t_1 = time to unload one unit freight, in hours per ton;
- t_2 = time to stop, in hours;
- t_3 = time for walking the length of a zone with a cart, in hours.
- V = average boat speed, in miles per hour.

The first two terms are independent of the number of stops. They represent the running time and the boat unloading time, respectively. The third term represents the maneuver time and the fourth term, that part of the cart delivery time that depends on N_{stop}. The latter refers to the distance that runs lengthwise with the canals; the transversal distance, instead, is independent of the number of stops. The solution of this equation is trivial if N_{stop} were a continuous variable. As it is well known, however, the continuous solution is an excellent approximation of the discrete one, so that the time consumed by the stop is $\sqrt{2t_2t_3}$. This quantity is small when the delivery zones themselves are small in size.

5. Conclusions

This research consists of the evaluation of different strategic decisions related to the reorganization of the freight distribution system in Venice. Different scenarios for the truck/boat transshipment are developed in order devise the most suitable organization of the operations involved with the modal split. We described a criterion for an efficient boat distribution that takes into account the different types of boats. Finally, we presented a model for the estimation of the optimal number and location of boat stops. Further research should address the details of an operating plan and the design of a warehouse, consistent with these ideas.

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