ABSTRACT

In this paper, the choice between different freight transportation modes is analyzed from the viewpoint of a shipper/receiver. The analysis is based on the concept of *total logistics costs*. This means that, when comparing different transportation modes, not only the cost of transportation itself should be considered by the shipper, but also all other costs in the supply chain that are affected by the choice of transportation mode.

The concept of total logistics costs is illustrated by means of a case study, in which a comparison is made between road haulage and inland navigation for the transport of bulk goods. The trade-off between transportation costs and inventory costs is made explicit, i.e. while inland navigation has lower transportation costs than road haulage, its inventory costs are higher. Due to the fact that the goods considered are of relatively high value, the lower transportation costs of inland navigation are more than offset by its higher inventory costs.

Keywords: transport, logistics, modal choice, inventory theory, case study

1. INTRODUCTION[1]

Models of modal choice in freight transportation can be categorized into different areas. Cunningham (1982, p. 66) distinguishes the following four categories: (i) the traditional approach, (ii) the revealed preference approach, (iii) the behavioural approach and (iv) the inventory-theoretic approach. This paper exclusively deals with those models belonging to Cunningham's (1982) fourth category [1]. An inventory-theoretic model of freight transportation is a model that attempts to analyze modal choice based on the concept of *total logistics costs* (cf. Ballou, 1999; Coyle *et al.*, 1996). This means that, when comparing different freight transportation modes, a shipper/receiver should not only consider the cost of transportation itself, but also take into account all other costs in the supply chain that are affected by the choice of transportation mode. Examples of these so-called *non-transportation logistics costs* are the costs of goods handling, packaging, inventory carrying, stock-outs, facility location, etc [2].

Or stated in the words of De Hayes (1969): "The choice of transport mode directly affects all other elements of the logistics system (e.g. packaging, production, planning, warehousing, facility location, information processing and inventory control). Consequently, the transport method must be selected to provide for efficient operation of the entire system." (quoted in Bardi, 1973, p. 23-24).

In a study conducted by the Flemish Economic Alliance (1999) with respect to the so-called *alternative modes* for freight transportation [3], it is shown that, besides the pure transportation costs, shippers also consider reliability, flexibility and average delivery time of a transportation mode as being very important factors when making a modal choice decision. Factors of secondary importance are safety, capacity, density of the transport network, regulation/legislation and environmental considerations [4].

While it is clear that not all of these elements can be expressed and modelled in terms of logistics costs, some elements can. This will be illustrated in the following sections. In

section two, a literature review is given on the inventory-theoretic approach towards modal choice in freight transportation. This literature review will lead us to the development of a total logistics costs model. The resulting model will in turn be used in section 3, in which a case study, partially based on real-market company data, is presented. In section 4 the main findings will be summarized and some avenues for further research suggested.

2. LITERATURE REVIEW

The work by Baumol and Vinod (1970) on the inventory-theoretic approach towards modal choice in freight transportation may be considered pathfinding. In their paper, the choice process of a transportation mode is shown to involve a trade-off among the following variables: (i) freight rates, (ii) average delivery time, and (iii) variance in delivery time.

The total logistics costs (TLC) of a transportation mode are formulated as follows (Baumol and Vinod, 1970, p. 419):

$$\text{TLC} = r.T + u.t.T + \frac{a}{s} + \frac{w.s.T}{2} + w.K \sqrt{(s+t).T} \qquad (1)$$

Where TLC = total logistics costs of a transportation mode (on an annual basis)
r = transportation cost per unit (including freight rate, loading and unloading, insurance,…)
T = total amount transported per year (in units)
u = in-transit carrying cost per unit per year
t = average time needed to complete a shipment (in years)
a = cost of ordering and processing per shipment
s = average time between shipments (in years)
w = warehouse carrying cost per unit per year
K = a constant, depending on the specified probability of no stock-outs during lead time

The first term in relation **(1)** refers to the annual transportation costs incurred by the shipper (sometimes these costs are referred to as the *out-of-pocket* costs). In the second

term the annual in-transit carrying costs are added. The next term indicates the annual ordering costs. The fourth term points to the inventory carrying costs at the destination, excluding the costs of safety stock. These costs of safety stock are given in the last term.

Clearly, Baumol and Vinod's (1970) approach takes account of both transportation costs and inventory costs. In what follows, the different components of the total logistics costs will be briefly discussed. Emphasis is placed on the relation between these costs and the modal choice decision.

2.1   Transportation costs

As far as the transportation costs are concerned, Baumol and Vinod (1970) assume a constant shipping cost *r* per unit. In other words, transportation costs do not vary with volume per shipment or with distance. Obviously, this assumption is not very realistic. In reality, due to the existence of *economies of scale*, transportation costs per unit decrease with increasing shipment size [5].

In order to solve this problem, Langley (1980) adapts the model of Baumol and Vinod (1970) by describing a number of alternative relationships between the quantity shipped and the transportation cost per unit. If Q represents the Economic Order Quantity (EOQ), the following relationships can be formulated (Langley, 1980, pp. 112-117):

(i)   a proportional relationship: $r = a - bQ$

(ii)   an exponential relationship: $r = a + bc^Q$ with $0 < c < 1$

(iii)   an inverse relationship: $r = a + \dfrac{b}{Q}$

(iv)   a discrete relationship, where per unit transportation rates are constant over specific ranges of Q, and decrease as certain minimum shipment volumes are reached [6].

It is obvious that from the viewpoint of the transportation costs only, a rational shipper would always choose the mode with the lowest transportation costs. As mentioned before, however, a comparison of different modes should not be limited to a comparison of just one criterion (i.e. transportation costs). Other logistics costs have to be taken into

consideration as well. A good example of these so-called *non-transportation logistics costs* are the inventory costs.

2.2   Inventory costs

The total inventory costs consist of four elements, i.e. (i) order costs, (ii) costs of inventory in transit, (iii) cycle stock costs, and (iv) safety stock costs.

2.2.1   *order costs*

The calculation of the annual order costs is rather straightforward: since s is the average time between shipments (in years), $1/s$ orders are placed every year, with an associated order and processing cost of a per order.

Clearly, one can reduce the annual order costs by keeping the annual number of orders low, i.e. shipping goods in large quantities. The impact of these costs, however, should not be overestimated. In most cases nowadays, the order and processing costs only play a minor role in the total logistics costs. With the introduction of large-scale automation and computerization in logistics, ordering and processing have indeed become much less labour-intensive (Blauwens *et al.*, 2001, p. 263).

Another way to reduce the order costs, is grouping orders for different parts into one large shipment *(consolidation)*. In this case, the aggregate order cost is less than the sum of the individual order costs when the items are ordered separately.

However, when considering whether or not to consolidate items into a larger shipment size, one has to keep in mind that this has an effect on a whole series of logistics costs. Not only the order costs are affected, but also transportation costs and inventory costs [7].

2.2.2   *costs of inventory in transit*

According to Baumol and Vinod (1970, p. 415), "freight in transit can be considered to be, in effect, an inventory on wheels, a working capital inventory perfectly analogous with goods in process in the factory".

The calculation of these costs is also straightforward. Multiplying the in-transit inventory cost per unit per year u by the average time (in years) to complete a shipment t yields the in-transit inventory cost per shipment. Multiplying this figure by the number of shipments yields the annual in-transit inventory costs.

It is obvious that the in-transit inventory costs encourage the use of fast transportation modes, such as road haulage or air transport. The premium one normally has to pay for this faster service is a higher transportation cost, as compared to, for example, rail transport or inland navigation (see also Ballou, 1999, p. 139).

2.2.3 *cycle stock costs*

As can be noted in relation **(1)**, average cycle stock at the destination is equal to half the shipment size: $s.T$ units are delivered each time, with these units gradually being used up until the next shipment arrives [8]. Multiplying this average inventory by the annual warehouse carrying cost w gives us the annual cycle stock costs at the destination. In the case where there exists cycle stock at the origin as well (e.g. as a result from goods being assembled and waiting to be shipped to the destination), the fourth term in **(1)** would double to $w.s.T.$ (see also Larson, 1988).

Baumol and Vinod (1970) do not include cycle stock at the origin in their cost model. In this respect, Sheffi *et al.* (1988) argue that, if the origin is sending goods to many different destinations, resulting in an outbound shipment frequency that is much higher than the inbound shipment frequency at each of the destinations, cycle stock at the origin can indeed be neglected (Sheffi *et al.*, 1988, p. 144-145) [9].

While the in-transit inventory carrying costs encourage the use of *fast* transportation modes (cf. supra), the cycle stock costs encourage the use of transportation modes with *small capacities*. After all, the use of such modes decreases the average time between shipments s, which in turn decreases the cycle stock costs (cf. **(1)**). Given that fast transportation modes normally transport small quantities (e.g. air transport), the distinction between these two logistics costs is not always clear. In essence, however, these two elements are of a completely different nature and should not be confused (Blauwens *et al.*, 2001, p. 248).

2.2.4 *safety stock costs*

A final element of the inventory costs are the costs incurred by holding safety stock or buffer stock at the destination. The safety stock is the inventory a company holds in addition to cycle stock as a buffer against delays in receipt of orders or changes in customer buying patterns. Holding safety stock may help a firm to avoid the negative, customer-related consequences of being out of stock (Coyle *et al.*, 1996).

Assuming that the stochastic elements in their problem satisfy a Poisson distribution, Baumol and Vinod (1970) calculate the safety stock as follows (see also Whitin, 1953, p. 42-56):

$$K.\sqrt{(s+t).T} \qquad \textbf{(2)}$$

Two important parameters for determining the safety stock are the average lead time *t* and the average time between shipments *s*. The larger these two variables, *ceteris paribus*, the larger the safety stock. The parameter *K* is a so-called *Poisson multiplier* (Larson, 1988, p. 43).

Das (1974, p. 183) argues that the Poisson-assumption may be inaccurate and, if not satisfied, results in an overestimation of the required level of safety stock. Therefore, an alternative way to compute the safety stock is needed. A useful approach is to assume that the safety stock is a function of *demand during lead time*, which in turn is dependent on the distribution of lead times and the distribution of demand during a fixed interval, assuming that all distributions are stationary and independent (Cawdery, 1976, p. 971) [10].

Under the assumptions that demand during lead time is normally distributed [11] and that the shortage criterion is to keep the probability of stock-out during any lead time period below a specified value *p*, the level of safety stock can be calculated as follows (see also Fetter and Dalleck, 1961, pp. 105-108):

$$SS = K.\sigma \qquad \textbf{(3)}$$

Where $SS =$ safety stock

$K =$ the so-called *safety factor*, i.e. the value such that the area under the standard normal curve to the right of K is equal to p (defined above)

$\sigma =$ the standard deviation of demand during lead time

In essence, the calculation of safety stock involves the computation of two elements: K and σ.

computation of K

It is obvious that the necessary level of safety stock increases with decreasing probabilities of stock-out during lead time and vice versa. To illustrate, table I gives an overview of some values for p and K.

TABLE I: SOME VALUES FOR *P* AND *K*

p	K	p	K
50%	0,00	4%	1,75
40%	0,25	3%	1,88
30%	0,52	2%	2,05
20%	0,84	1%	2,33
10%	1,28	0,50%	2,58
5%	1,64	0,05%	3,30

Source: Blauwens *et al.*, 2001, p. 256

From table I, it can be seen that if one is willing to accept a stock-out during lead time with a probability of 50%, there is no need to hold any safety stock ($K = 0$). In this case, a shipment is planned to arrive when inventory level has fallen to zero. Hence, in one out of two cases, there will be a shortage prior to shipment arrival.

Reducing the probability of stocking out during lead time to 40% requires a safety stock that is 0,25 times the standard deviation of demand during lead time. Reducing it even further to 30% requires about a doubling of this safety stock level (K-value of 0,52). If a stock-out may only occur in 5% of the cases, the safety stock increases to 1,64 times the standard deviation of demand during lead time. If one is only willing to accept a risk of

stock-out of e.g. 0,05% (i.e. a stock-out only occurs once every 2.000 deliveries), safety stock should be equal to 3,30 times the standard deviation of demand during lead time.

computation of σ

The standard deviation of demand during lead time can be computed as a function of four variables, namely (i) average lead time M_t, (ii) variance of lead time V_t, (iii) average demand M_d and (iv) variance of demand V_d. In essence, two cases can be distinguished.

(i) lead time is independent from demand

If lead time is independent from demand and demand itself is not autocorrelated [12], the standard deviation of demand during lead time can be computed as follows (Das, 1974, p. 184):

$$\sigma = \sqrt{M_t V_d + M_d^2 V_t} \qquad \textbf{(4)}$$

Gross and Soriano (1969, p. 68-69) provide another way of determining the standard deviation of demand during lead time. It is computed as follows:

$$\sigma = \mu_d \sqrt{\mu_t v_d^2 + \mu_t^2 v_t^2} \qquad \textbf{(5)}$$

Where μ_t = average lead time

v_t = coefficient of variation of the lead time (not to confuse with V_t)

μ_d = average demand

v_d = coefficient of variation of demand (not to confuse with V_d)

In contrast to the standard deviation $\sigma(.)$, which is an *absolute* measure of the dispersion of a set of numbers, the coefficient of variation $v(.)$ is a *relative* measure of this dispersion. It allows us to consider the dispersion as a proportion of the mean (Aczel, 1993, p. 38). The formula for $v(.)$ is equal to

$$v(.) = \frac{\text{standard deviation}}{\text{average}} = \frac{\sigma(.)}{u(.)} \qquad \textbf{(6)}$$

A large v-value characterizes a situation where the fluctuations in the variable considered are large in comparison to the average of the variable. From the above formulas it is clear that even if lead time variability increases sligthly, the resulting increase in safety stock should not be neglected (see also Bramson, 1962; Zinn and Marmorstein, 1990).

It is easy to verify that formulas **(4)** and **(5)** are exactly the same. If we replace v_t by $\frac{\sqrt{V_t}}{M_t}$ and v_d by $\frac{\sqrt{V_d}}{M_d}$, we obtain

$$\sigma = M_d \sqrt{M_t \left(\frac{\sqrt{V_d}}{M_d}\right)^2 + M_t^2 \left(\frac{\sqrt{V_t}}{M_t}\right)^2}$$

which leads to

$$\sigma = \sqrt{M_d^2 M_t \left(\frac{\sqrt{V_d}}{M_d}\right)^2 + M_d^2 M_t^2 \left(\frac{\sqrt{V_t}}{M_t}\right)^2} = \sqrt{M_t V_d + M_d^2 V_t}$$

(ii) lead time is not independent from demand

If lead time is not independent from demand, the computation of σ is somewhat different, namely (Allen *et al.*, 1985, p. 455):

$$\sigma = \sqrt{M_t^2 V_d + M_d^2 V_t + \sigma_t \sigma_d} \qquad \textbf{(7)}$$

Where σ_t and σ_d represent the standard deviation of lead time and of demand, respectively, and all other elements are defined above.

Formulas **(4)** and **(7)** show the impact of both the speed and the reliability of a transport mode on safety stock: the faster and the more reliable a transport mode (the smaller M_t and V_t), *ceteris paribus*, the smaller the safety stock which is needed at the destination (see also Tyworth, 1991). If, in the extreme (but unrealistic) case, M_t and V_t would both be equal to zero, there would be no need to hold safety stock (cf. the concept of *just-in time deliveries*). It is obvious that a stockout during lead time cannot occur in a situation where lead time is always zero. In this case, order arrivals would coincide with the point in time where stock level reaches zero (Howard, 1974/75, p. 97).

using the variance of forecast errors instead of the variance of demand

Zinn and Marmorstein (1990) compare two alternative methods to determine the level of safety stock. In the first method, the so-called *Demand System*, the level of safety stock depends on the *variability of demand*. It is computed as $K.\sigma$ with σ determined as in relation **(4)**.

The second method, called the *Forecast System*, uses the *variability of demand forecast errors* as a basis to determine safety stock levels. Safety stock is computed as

$$K . \sqrt{M_t V_f + M_d^2 V_t} \qquad \textbf{(8)}$$

Where V_f represents the variance of forecast errors (the other elements are defined above). As one can see, the only difference is that, in the second method, the variance of demand V_d is substituted by the variance of the forecast errors V_f. All other parameters remain the same. Nevertheless, the authors argue that there is a substantial difference between the two systems: "Simulation results indicate that the Forecast System, albeit less prominent in the logistics literature, typically requires about 15% less safety stock to provide the same level of customer service" (Zinn and Marmorstein, 1990, p. 96) [13].

the assumption of normality of demand during lead time

From the above, it is clear that modelling the distribution of demand during lead time is essential to evaluate the effects of speed and consistency of delivery on inventory holding costs (Tyworth, 1991, p. 304).

In the inventory literature, two basic methods of modelling the lead time demand distribution are identified. One method is to model this distribution directly from empirical data. Although this can be a reasonable approach, potential limitations make it undesirable for theoretical and practical reasons (Tyworth, 1991; Bagchi *et al.*, 1984; Silver and Peterson, 1985).

The other method is to model the lead time and demand elements individually, and then construct a *compound statistical distribution* of demand during lead time (Tyworth, 1991; Tyworth, 1992; McFadden, 1972; Mentzer and Krishnan, 1985; Bagchi and Ord, 1983; Bagchi *et al.*, 1984; Bagchi *et al.*, 1986). In this respect, Lu *et al.* (1962, p. 503) argue that "if both demand and lead time are stochastic, it is usually more convenient to collect the necessary data for estimating the means of demand (per unit time) and lead time than estimating directly the mean and the standard deviation of demand during lead time".

The conventional procedure used in transportation selection models to estimate the effects of average lead time and lead time variability on inventory costs is as follows (Tyworth, 1991, p. 304): assuming that demand during lead time is normally distributed, Fetter and Dalleck's (1961) "numerical method" can be used to calculate the mean and standard deviation of demand during lead time. Following inventory theory, the safety stock can then be calculated as proportionate to the standard deviation of demand during lead time (see relation **(4)**).

Although widely used in the literature, Tyworth (1991) indicates some important conceptual and practical limitations to this second approach.

First of all, "almost all transportation selection models that deal with stochastic lead time and demand, bypass efforts to model demand and lead time to construct the compound distribution of demand during lead time". Instead, "they directly assume that demand

during lead time is normally distributed and that one can estimate the mean and variance of both lead time and demand (…) This approach is very useful from a practical viewpoint, since it eliminates the need to model the functional form of demand and lead time to construct lead time demand" (Tyworth, 1991, p.308) [14].

However, "the use of the normal distribution to characterize lead time demand is, in general, unwarranted". In effect, "the theoretical or empirical justification for the general use of the normal distribution assumption is lacking". Moreover, "incorrectly assuming that demand during lead time is normally distributed can be costly" (Tyworth, 1991, p. 308-309) [15].

According to Tyworth (1992, p. 102), "the difficulties involved in evaluating non-normal shapes of the lead time demand distribution through the use of convolution procedures makes the normal distribution a convenient refuge." However, "the lead time demand distribution is prone to have a non-normal shape. Studies show, for example, that the distributions of transit time are often positively skewed and are subject to systematic 'weekend' effects – two characteristics that undermine the normality assumption [of demand during lead time]".

In this respect, Mentzer and Krishnan (1985) argue that the assumption of a normal distribution for the demand during lead time is not valid, since the normal distribution is defined between $-\infty$ and $+\infty$ and this can create the probability of negative demand [16].

Therefore, there exist many other assumptions concerning the distribution of demand during lead time. Examples include the negative binomial distribution, resulting from a poisson distributed demand and a gamma distributed lead time (Cawdery, 1976) [17] and an approximate gamma distribution, resulting from a normally distributed demand and gamma distributed lead time (Tyworth, 1991) [18].

Kottas and Lau (1979) have developed an approach in which a four-parameter distribution is used to characterize demand during lead time. Such a distribution has more capability to fit diverse non-normal shapes than distributions with fewer parameters (Tyworth, 1992, p. 102). Tyworth (1992) goes a step further, in that he presents a "paradigm shift" in which the technically difficult task of constructing a compound distribution of demand during

lead time is no longer required. Instead, his method is based on the convex combination of period demand distributions constructed over the range of possible lead times. When certain conditions are met, Tyworth's (1992) approach enables one to accurately estimate the effects of speed and consistency on safety stock *without* knowledge of the shape of the lead time demand distribution. This is a major advance (Keaton, 1995, p. 107).

Second, Tyworth (1991, p. 311) argues that an explicit distinction should be made between shipping time and lead time: "lead time includes both ordering time and shipping time. Ordering time, which comprises preparation, transmittal and processing elements, may represent 40 per cent or more of the lead time". Therefore, "by treating shipping time as lead time, transportation selection models underestimate lead time and thus the standard deviation of demand during lead time (…) The result is an underestimation of safety stock costs" [19].

2.3   Trade-offs between transportation and inventory costs

From the above discussion it should be clear that, in many cases, a trade-off exists between transportation costs and inventory costs: if one wants to cut transportation costs by shipping in large quantities with a slow transportation mode (for example inland navigation instead of road haulage), one has to keep in mind that this leads to an increase in both the in-transit inventory costs and the inventory costs at the destination (i.e. cycle stock and safety stock) [20]. For an overview of other cost trade-offs in logistics, the reader is referred to Herron (1975, p. 253).

Lang *et al.* (2000) analyze the trade-off between transportation costs and inventory carrying costs for the case of road haulage versus rail transport. They argue that "if the rate of use of the product is high and the value of the product is relatively low, the additional inventory associated with the larger rail shipment sizes can be more than offset by their lower transport costs. If, on the other hand, the value of the product is high and it is used slowly, the cost of additional inventory associated with a large rail shipment size may exceed the differential in transport rates between truck and rail" (Lang *et al.*, 2000, p. 4; see also Swan and Tyworth, 2001). In the present paper, the effect of the value of the goods on the total logistics costs is analyzed in the case study (see section 3).

Similar "Total Logistics Costs" models as the one developed by Baumol and Vinod (1970) can be found in Buffa and Reynolds (1977), Constable and Whybark (1978), Liberatore (1979), Buffa and Reynolds (1979), Langley (1980), Blumenfeld *et al.* (1985a), Allen *et al.* (1985), McFadden *et al.* (1985), Buffa (1986a), Sheffi *et al.* (1988), Larson (1988), Perl and Sirisoponsilp (1988), Tersine *et al.* (1989), Tyworth (1991), Allen and Liu (1993), Tyworth and O'Neill (1997), Tyworth and Zeng (1998) and Swan and Tyworth (2001).

The model developed by Constable and Whybark (1978) is very similar to that of Baumol and Vinod (1970). However, there is one big difference as far as the safety stock is concerned. Rather than assuming the existence of a specific level of safety stock to account for uncertainty in demand forecasts and delivery time, Constable and Whybark (1978) incorporate a *backorder cost function* in their model (Langley, 1980, p. 109) [21].

In Blumenfeld *et al.* (1985a) a distinction is made between direct shipping from origin to destination on the one hand and shipping via a consolidation terminal on the other. Transit times and demands are assumed fixed, so safety stock issues are not considered explicitly. Buffa (1986a) also evaluates alternative plans to consolidate inbound freight. His total logistics cost model includes (i) transportation costs (i.e., shipping cost and in-transit holding cost), (ii) consolidation costs (order cost and handling and storage costs at the consolidation terminal), and (iii) inventory costs (purchasing, ordering, holding and stockout costs). Three alternative plans for consolidation are studied, with each plan having a different impact on total logistics costs [22].

3.   A CASE STUDY

In this section, a case study is presented in which the concept of total logistics costs is illustrated. The case study deals with a shipper who currently uses road haulage for incoming bulk goods, but who is planning to switch modes to inland navigation for some of these goods flows. The case study is partially based on real-market company data. Due to confidentiality reasons, the name of the company and the commodity type cannot be disclosed.

Whether or not the modal shift to inland navigation is justified from the viewpoint of total logistics costs will be analyzed in the following paragraphs. First, the transportation costs of both modes are discussed. Then the inventory carrying costs are calculated. The fixed costs are discussed thereafter. The starting data are presented in table II.

TABLE II : CASE STUDY DATA

	Road haulage	Inland navigation
Shipment size	25 tonnes	1,200 tonnes
Transportation costs	10.91 euro per tonne	8.43 euro per tonne
Average lead time	0.19 days	4.48 days
Lead time variance	proportionate with average lead time	
Value of the goods	620 euro per tonne	
Inventory costs	93 euro per tonne	
fixed costs	0.09 euro per tonne	0.45 euro per tonne
Annual volume	55,000 tonnes	

Note: 1 euro ≅ 0.9 US $

3.1   Transportation costs

As can be seen from table II, a modal shift from road haulage to inland navigation enables the shipper to economize on the transportation costs. Shipping the goods in a 1,200-tonne barge is more than 20% cheaper than road haulage.

Hence, based on the transportation costs only, no rational shipper would choose to transport the goods by truck in this specific situation. As mentioned before, however, a comparison of freight transportation modes should not be limited to a comparison of their transportation costs. There are other costs in the supply chain that are affected by the

choice of transportation mode and that have to be taken into consideration as well. In the following paragraphs, we discuss the inventory carrying costs and the fixed costs. It will be shown that these costs, contrary to the transportation costs, play to the disadvantage of inland navigation.

3.2 Inventory costs

The cost of keeping goods in inventory comprises four elements (Blauwens *et al.*, 2001; Lambrecht, 1999; van Goor *et al.*, 2000): (i) interest costs, (ii) depreciation costs, (iii) insurance costs and (iv) warehousing costs.

In this specific case study, the annual inventory costs amount to 15% of the value of the goods. Since this value is 620 euro per tonne, inventory costs are 93 euro per tonne per year. This amount applies both to the inventory in transit and the inventory at the destination. We can now calculate the in-transit inventory costs, the cycle stock costs and the costs of safety stock.

3.2.1 *in-transit inventory costs*

The average lead time of road haulage, loading and unloading included, is about 4.5 hours or approximately 0.19 days. The in-transit inventory costs are therefore

$$0.19 \text{ days x } \frac{93}{365} \text{ euro per tonne per day} = 0.05 \text{ euro per tonne.}$$

Of course, transport by inland navigation requires a longer transit time. Based on revealed facts, the average lead time of this transportation mode amounts to 4.48 days, loading and unloading included. This rather long lead time can be explained by the fact that the barge has to pass quite a lot of locks on its route, which inevitably leads to waiting times. In addition, there are waiting times due to regulations that prohibit navigation on the channels on particular days of the week. The in-transit inventory costs for inland navigation can be calculated in the same manner as we did for road haulage. They amount to 1.14 euro per tonne.

3.2.2 *cycle stock costs*

As discussed above (see relation **(1)**), the average cycle stock at the destination is equal to half the shipment size. It is clear that this has an impact on the modal choice decision. In the current situation, i.e. using road haulage in 25-tonne trucks, the average cycle stock is 12.5 tonnes. This leads to cycle stock costs of

12.5 tonnes x 93 euro per tonne per year = 1,163 euro per year.

Since the annual volume to be transported is 55,000 tonnes, the cycle stock costs are 0.02 euro per tonne.

When switching to inland navigation, cycle stock costs will of course rise. Shipping in quantities of 1,200 tonnes makes that on average 600 tonnes are in cycle stock. This in turn leads to cycle stock costs of 55,800 euro per year or 1.01 euro per tonne.

3.2.3 *safety stock costs*

In the current situation, the safety stock at the shipper's premises is 250 tonnes. This safety stock should be seen in relation to the total incoming goods flow, which is 127,000 tonnes. Safety stock costs are therefore equal to 23,250 euro per year or 0.18 euro per tonne.

We now have to calculate how this safety stock should be adapted when the shipper decides to make the modal shift to inland navigation. Assuming that demand during lead time is normally distributed and that the shipper does not wish to accept a higher risk of running out of stock when making the modal shift, the safety stock for inland navigation can easily be derived from the safety stock for road haulage. This is illustrated in the following calculations.

Recall from relations **(2)** and **(3)** that the level of safety stock can be calculated as

$$SS = K.\ \sigma$$

Where $SS =$ safety stock

      $K =$ the safety factor

      $\sigma =$ the standard deviation of demand during lead time $= \sqrt{M_t V_d + M_d^2 V_t}$

Switching from road haulage to inland navigation only affects the average lead time M_t and the lead time variance V_t. There is no reason to assume that average demand M_d and variance in demand V_d will be affected by the modal choice decision.

Since we have no data on the lead time variance for road haulage, we make the (neutral) assumption that this lead time variance is proportionate to the average lead time.

Since the average lead time increases from 0.19 days to 4.48 days when switching from road haulage to inland navigation, both M_t and V_t are multiplied by (4.48/0.19) = 23.58. As a consequence, the standard deviation of demand during lead time is multiplied by $\sqrt{23.58} = 4.86$.

This means that, in order to keep the risk of a stockout constant, the safety stock should be increased from 250 tonnes in the case of road haulage to (250 x 4.86) = 1,214 tonnes in the case of inland navigation. This leads to safety stock costs of 112,902 euro per year or 0.89 euro per tonne.

3.3   Fixed costs

A final element of the total logistics costs are fixed costs, i.e. costs that do not vary with the level of stock. These costs consist of investments in infrastructure (construction of an unloading quay) and superstructure (unloading equipment and a large warehouse to store the goods) and warehouse insurance costs [23]. Taking into account these investments and the appropriate depreciation terms, it was found that fixed costs equalled 0.09 euro per tonne for road haulage and 0.45 euro per tonne for inland navigation (see table II).

3.4   Total logistics costs

On the basis of the elements described and calculated above, we can now calculate the total logistics costs for road haulage and inland navigation. These total logistics costs, which comprise transportation costs, inventory costs and fixed costs, are presented in table III.

TABLE III : TOTAL LOGISTICS COSTS FOR ROAD HAULAGE AND INLAND NAVIGATION (ALL COSTS ARE PER TONNE)

	Road haulage	Inland navigation
Transportation costs	10.91 euro	8.43 euro
In-transit inventory costs	0.05 euro	1.14 euro
Cycle stock costs	0.02 euro	1.01 euro
Safety stock costs	0.18 euro	0.89 euro
Fixed costs	0.09 euro	0.45 euro
Total Logistics Costs	**11.25 euro**	**11.92 euro**

It can be seen from table III that, despite its significantly lower transportation costs, inland navigation turns out to be the more expensive transportation mode from the viewpoint of total logistics costs. Its advantage in transportation costs is more than offset by its disadvantage in inventory costs. This can be explained by the fact that the bulk goods considered are of relatively high value (620 euro per tonne).

Table IV indeed shows that for goods with a lower value, transport by inland navigation is actually cheaper than road haulage. In the case of bulk goods with a value of 50 euro per tonne, e.g., inland navigation is about 17% cheaper than road haulage. As the value of the goods increases, the gap between both transportation modes narrows. The *break-even* value of the goods, i.e. the value where both modes have the same total logistics costs, is about 470 euro per tonne. From this point onwards, the balance turns in favour of road haulage (see also figure 1). For bulk goods with a value of 1.000 euro per tonne, e.g.,
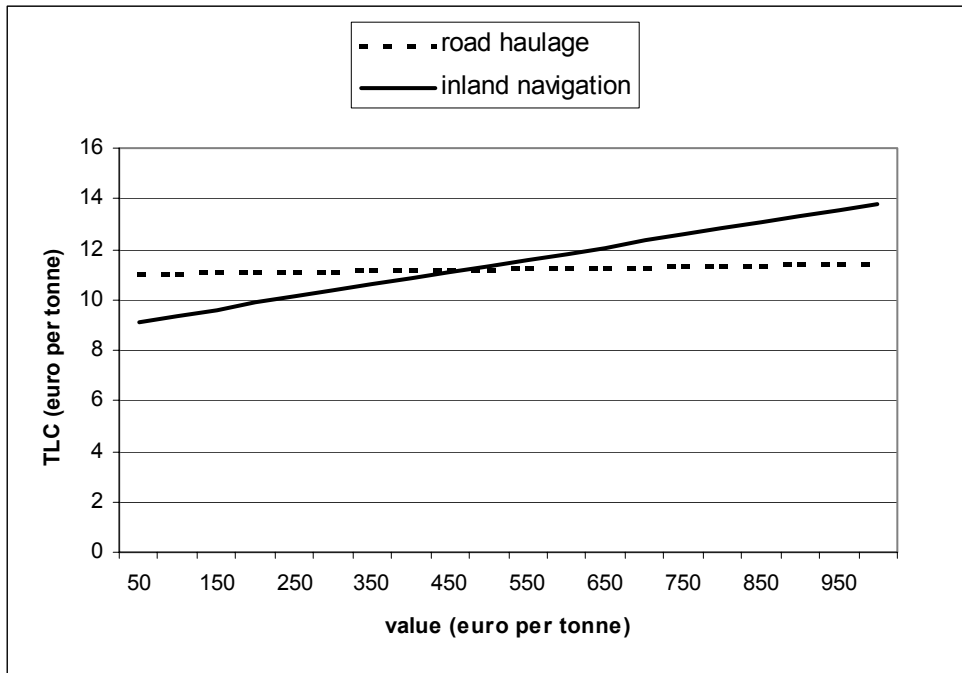
inland navigation would be about 20% more expensive than road haulage in this specific situation.

TABLE IV : TOTAL LOGISTICS COSTS (TLC) AS A FUNCTION OF THE VALUE OF THE GOODS

Value (euro per tonne)	TLC Road haulage	TLC Inland navigation	Δ TLC (euro per tonne)
50	11.02	9.13	17.19%
100	11.04	9.37	15.12%
150	11.06	9.62	13.06%
200	11.08	9.86	11.00%
250	11.10	10.11	8.95%
300	11.12	10.35	6.91%
350	11.14	10.60	4.88%
400	11.16	10.84	2.85%
450	11.18	11.09	0.83%
500	11.20	11.34	-1.18%
550	11.22	11.58	-3.18%
600	11.24	11.83	-5.18%
650	11.26	12.07	-7.17%
700	11.29	12.32	-9.15%
750	11.31	12.56	-11.13%
800	11.33	12.81	-13.09%
850	11.35	13.05	-15.06%
900	11.37	13.30	-17.01%
950	11.39	13.55	-18.96%
1.000	11.41	13.79	-20.90%

Note: $\Delta \text{TLC} = \dfrac{\text{TLC road haulage - TLC inland navigation}}{\text{TLC road haulage}} \times 100\%$

4. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

In this paper, the choice between different freight transportation modes was analyzed from an inventory-theoretic perspective. The analysis was based on the concept of *total logistics costs*, which means that all costs in the supply chain that are affected by the choice of transportation mode should be taken into consideration when making a modal choice decision.

The concept of total logistics costs was illustrated by means of a case study, in which a comparison was made between road haulage and inland navigation for the transport of bulk goods. The trade-off between transportation costs and inventory costs was shown: while inland navigation had lower transportation costs than road haulage, its inventory costs were higher. Due to the fact that the goods considered were of relatively high value, the lower transportation costs of inland navigation were more than offset by its higher inventory costs.

A crucial assumption underlying the total logistics costs model presented at the beginning of this paper and used in the case study, was the normal distribution of demand during lead time. Under this assumption, safety stock could easily be calculated as proportionate to the standard deviation of demand during lead time.

However, a number of previous studies have criticized this assumption on the grounds that it can lead to serious errors in safety stock. This is certainly an area for further research. In further publications, we would therefore like to report on the issue of non-normally distributed lead time demand.

Yet, the impact of a misspecification of safety stock on total logistics costs should not be overestimated. In the case study, safety stock costs represent only 1,6% and 7,4% of the total logistics costs for road haulage and inland navigation, respectively. Even in the case of high value bulk goods (i.e. a value of 1,000 euro per tonne), safety stock costs would represent only 2,6% and 10,4% of the total logistics costs for road haulage and inland navigation, respectively. So even if there is a large misspecification of safety stock, this would not seriously affect the total logistics costs.

ENDNOTES

[1] For a detailed discussion of all four categories, we refer to Cunningham (1982). Other ways of categorizing freight demand models can be found in Winston (1983) or McGinnis (1989).

[2] According to Perl and Sirisoponsilp (1988, p. 22), transportation decisions can be classified into three hierarchical levels of managerial logistics decisions. The choice of a transportation mode and the choice of type of carriage is considered a *strategic* transportation decision. The selection of a specific carrier within the chosen mode and the determination of shipment frequency (or shipment size) is a *tactical* transportation decision. Finally, typical transportation decisions at the *operational* level include the assignment of loads to vehicles and the routing and scheduling of vehicles and crews.

[3] In the context of freight transportation, an *alternative* mode is any mode other than road haulage (for example inland navigation, rail transport, air transport, shortsea transport, etc).

[4] See also Bardi (1973), Saleh and Das (1974), Evans and Southard (1974), Gilmour (1976), Stock and La Londe (1977), Piercy and Ballou (1978), McGinnis *et al.* (1981), Chow and Poist (1984), Bagchi *et al.* (1987), McGinnis (1989), McGinnis (1990), Jeffs and Hills (1990).

[5] For a discussion of economies of scale in road haulage and inland navigation, see Blauwens *et al.* (2001, p. 127-142). One has to keep in mind that, as far as economies of scale are concerned, there can be differences between the *user* and the *producer* of transport. After all, the price paid by the shipper is not always a function of the cost to the carrier.

[6] For other assumptions regarding transportation costs per unit, see Sheffi *et al.* (1988), Tersine *et al.* (1989), Tyworth and Zeng (1998).

[7] For an overview of the effects of consolidation on total logistics costs, see Masters (1981), Jackson (1985) or Buffa (1986a, 1986b, 1987).

[8] See also Blumenfeld *et al.* (1985a, p. 364).

[9] See also Blumenfeld *et al.* (1985a, 1985b), Horowitz and Daganzo (1986) or Blauwens *et al.* (2001).

[10] See also McFadden (1972) and Danish (1972).

[11] This assumption has been criticized in the literature – cf. infra.

[12] Autocorrelation measures the extent to which values for a single variable are correlated over time. If demand is autocorrelated, this means that the demand observed in one particular day depends on the demand

in previous days. For a discussion of the effect of autocorrelation on customer service, see Zinn *et al.* (1992). See also Ray (1980).

[13] For other advantages of the Forecast System approach, the reader is referred to Tyworth (1992, p. 108).

[14] See also McFadden (1972), Eppen and Martin (1988), Lau (1989) and Tyworth (1992).

[15] See also Speh and Wagenheim (1978), Nahmias and Demmy (1982), Tadikamalla (1984), Eppen and Martin (1988), Lau (1989), Tyworth *et al.* (1991b), Tyworth (1992), Keaton (1995) and Tyworth and O'Neill (1997).

[16] See also Burgin (1975).

[17] See also McFadden (1972), Bagchi *et al.* (1986) and Danish (1972). It is important to notice that Cawdery (1976) and McFadden (1972) analyze lead time in the context of inventory control. Their papers, however, do not deal with modal choice in transportation. Lead time therefore does not include transportation times – cf infra.

[18] For an overview of other compound distributions of demand during lead time, see Bagchi *et al.* (1984, 1986). See also Bott (1977) and Lau (1989).

[19] See also Tyworth and Zeng (1998), Swan and Tyworth (2001) and Lau (1989).

[20] See also Ballou and DeHayes (1967), Buffa and Reynolds (1977), Burns *et al.* (1985), Blumenfeld *et al.* (1985b), Sheffi *et al.* (1988), Larson (1988); Arcelus and Rowcroft (1991)

[21] See also Allen *et al.* (1985), Blumenfeld *et al.* (1985b).

[22] See also Buffa (1986b) and Buffa (1987).

[23] As far as the construction of the unloading quay is concerned, the shipper can benefit from the so-called *80/20-regulation*. This is a form of public-private partnership (pps) between the shipper and the Flemish Government. The Government pays 80% of the investment in the quay, with the shipper paying the remaining 20%. In return, the shipper has to guarantee that a certain minimum volume will be transported by inland navigation. Through this form of cooperation, the Flemish Government wants to stimulate the transport by waterways.

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