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Freight distribution systems with cross-docking: a multidisciplinary analysis

Jesus Gonzalez-Feliu

Laboratoire d'Economie des Transports

ISH, 14 Av. Berthelot

69363 Lyon Cedex 07

France

Abstract

Freight transport constitutes one of the main activities that influences the economy and society, as it assures a vital link between suppliers and customers and it represents a major source of employment. Multi-echelon distribution is one of the most common strategies adopted by transport companies for cost reduction. This paper presents the main concepts of multi-echelon distribution with cross-docking through a multidisciplinary analysis that includes an optimization study and a socioeconomic analysis. The optimization analysis proposes both a geographic approach based on the concept of accessibility, and a scenario simulation analysis for collaborative freight transportation. The socioeconomic analysis includes a conceptual framework for logistics and transport pooling systems, as well as a simulation method for strategic planning optimization.

Keywords: Freight transport systems, outbound logistics, cross-docking, simulation, collaboration.

Freight distribution systems with cross-docking: a multidisciplinary analysis

1. Introduction

The freight transport industry is a major source of employment and supports the economic development of a country. However, freight transport has many negative aspects including congestion and environmental disturbance, which negatively affect quality of life (Crainic and Laporte, 1997). In recent years companies have changed their logistics strategies to better adapt them to changing demand. Moreover, new advances in technology have been positive factors in the development of new markets and new consumer needs, leading to the development of multi-echelon transport schemas (Rodrigue, 2006). A wide variety of fields have developed multi-echelon transportation approaches with cross-docking, for example in the *press distribution* sector, in the automotive industry, more precisely in *spare parts supply* distribution, in *parcel and postal distribution* and in *urban freight distribution* (Gonzalez-Feliu, 2011). Moreover, *intermodal transportation* (Lowe, 2005), specifically containerized distribution, is also a classical example of a multi-echelon system where freight is conserved unaltered from its departure to the arrival at its final destination. *Grocery distribution* is also a field which presents a heterogeneous group of supply chains, most of them are based on distribution systems presenting several echelons (TL&Associés and LET, 2009).

A multi-echelon transportation system is composed of at least two connected transportation schemes linked by at least one transshipment operation (Gonzalez-Feliu, 2011). According to Brewer et al. (2001), two strategies are used in such systems: cross-docking and warehousing. Multi-echelon transportation with cross-docking differs from that with warehousing in the fact that intermediary platforms do not have the possibility to stock, but allow the consolidation and transshipment operations (Beuthe and Kreuzinger, 2001). In a global economic situation where reactivity and adaptation to change are important factors of success, it is important to relate the technical and computational feasibility of a logistics solution to its socio-economic feasibility. These two concepts

are usually studied separately by different scientific communities, and the relations between them are very limited.

This paper aims to propose a multidisciplinary framework to conceptualize and study multi-echelon transport systems with cross-docking combining both mathematical modeling and socio-economics studies. More precisely, we propose a trans-disciplinary approach not only focusing on theoretical or technical aspects related to a specific field but also on its applicability and general feasibility. First, a review of the significant literature on multi-echelon systems with cross-docking is presented. Second, a mathematical model is proposed to conceptualize multi-echelon transportation cost optimization with cross-docking. Moreover, two cost optimization analysis are carried out to see the advantages and the potential of these systems. The first analysis derives from the application of the proposed model, by an accessibility analysis, to illustrate the case of a two-echelon transport system for a single carrier. The second is a scenario analysis for collaborative freight transportation using a fast heuristic method, to study the potential of collaboration among carriers to optimize transportation costs. In both analysis, the results are related to practical implications rather than to computational effectiveness. Finally, a socio-economic analysis is proposed in order to define the incentives and limitation factors to these approaches using a qualitative analysis from data collected by semi-directive interviews.

2. Literature review

In freight transport, decisions on the transport network settings have a direct impact on the service quality but also on their costs. It is then important to adapt the transport network to the economic, geographic, organizational and quality constraints. In the last years, several strategies and logistics models have been developed to increase effectiveness of freight transport systems (Wieberneit, 2008). Multi-echelon systems with cross-docking is one of the most popular, since it reduces logistics costs by avoiding inventory operations (Lambert, 2008). Moreover, it is the base of most collaborative transportation systems (Gonzalez-Feliu and Morana, 2011). In scientific literature, we find several fields and research subjects dealing with multi-echelon transportation with cross-docking. The main disciplines are operations research, business, management, socio-economics and transport engineering.

In transport engineering, the main research subjects deal with vehicle management at terminals (Wang and Regan, 2008) and intermodal transport management (Lowe, 2005; Dalla Chiara et al., 2008). These works are related to terminal and infrastructure management, and not to the management of the transportation system. Also in operations research we can find such works, mainly related to terminal management (Soltani et al., 2010; Larbi et al., 2011) or to infrastructural aspects of multi-echelon transportation (Aikens, 1985; Klose and Drexler, 2005). However, these categories of research works will not be detailed here because they refer to technical aspects of a part of the system, and are not related to multi-echelon transportation management.

In the last years, tactical and operational issues in multi-echelon transportation have become a major research subject. Most of the operations research works related to freight transport management derive from the Vehicle Routing Problem (VRP). It can be defined as a combinatorial optimization problem seeking to minimize the total transportation cost of delivering a number of customers with a fleet of vehicles that are based at one or more depots (Toth and Vigo, 2002). The problem has been proposed by Dantzig and Ramser (1959) and count many variants (Golden et al., 2008). Multi-echelon vehicle routing approaches aim to minimize the costs of both determine the location of intermediary facilities and construct a set of routes to deliver several final destinations using cross-docking platforms. (Laporte, 1988).

Wren (1971), Jacobsen and Madsen (1980), Brunswicker (1986) and Vahrenkamp (1989) propose several heuristics for real applications, in a simplified variant where only one cross-docking platform is used by each vehicle. In all cases, a constructive procedure is presented. In the first phase (clustering), customers are grouped and assigned to vehicles delivering the cross-docking platforms. The second phase (allocation) consists in determining, for each vehicle, one transshipment location. The third and last stage is the routing phase, where all routes are determined by classical heuristics that insert each destination on a suitable route. Semet and Taillard (1993) propose an algorithm which find an initial solution using a constructive procedure in a similar way than those presented above and improved by a procedure where customers can be reallocated on other routes. Gerdessen (1996), Chao (2002) and Schreuer (2006) propose algorithms that finds an initial solution using a combination of

heuristics like those proposed by Jacobsen and Madsen (1980), then improved by a procedure that reallocates the destinations using iterative local search heuristics (Laporte, 1992). Hoff and Løkketangen (2007) adapt these methods to solve a real optimization problem for milk collection in Norway. Boccia et al. (2010) and Nguyen et al. (2010) propose a procedure combining a constructive heuristic that builds each echelon routes separately and an improvement post-optimization algorithm based on route reallocation.

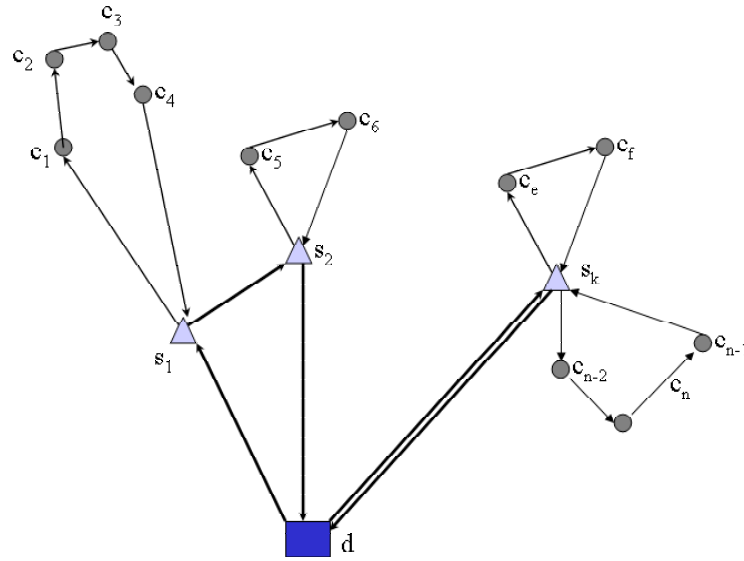


Figure 1 – An Example of a Two-Echelon Transportation System

Crainic et al., (2004) propose a method for planning related to urban freight distribution. More precisely, they deal with the definition of the optimal transport network, taking into account a number of pre-defined routes and management assumptions. Gendron and Semet (2009) propose a mathematical formulation for a similar problem, which is then solved using commercial tools. In both approaches, the routes delivering the final destinations are fixed, and the decisions arise on the construction of routes to deliver the cross-docking platforms and the location of these facilities.

Business and management issues are more related to the interaction between transportation and supply chain management (Kreng and Chen, 2008). Most of these works are related to multi-echelon system optimization, in the context of either general supply chains or distribution networks. A supply chain can be defined as the integrated set of processes related to product manufacturing and distribution that cover all the operations from raw material collection to final product delivery to customers (Beamon,

1998). According to Brewer et al. (2001), a supply chain is comprised of three integrated parts: (1) raw material collection and production supply, (2) production planning and inventory and (2) distribution to the final destination. In global supply chain works, decisions on supply, production and inventory are internal to the company, whereas distribution and transportation is usually externalized. For these reasons, many works in supply chain management focus on these other aspects and include transportation as additional costs without taking into account transport management and optimization analysis (Lambert, 2008). In distribution logistics, most works deal with multi-echelon distribution systems with warehousing, focusing on inventory management rather than on transportation planning (Brewer et al., 2001; Lambert, 2008). Regarding multi-echelon distribution with cross-docking, most works focus on production-distribution co-ordination (Galbreth et al., 2008). In these works, distribution costs are mainly associated to transport demand and to cross-docking platform management costs, not to the traveled distances or the chosen transport strategies.

Also qualitative studies deal with supply chain management and can be related to multi-echelon transportation with cross-docking. Yang et al. (2010) analyze the factors affecting cross-docking in a terminal management perspective, but including the impacts from other supply chain echelons such as delays on production and distribution. Paché (2008) proposes to study multi-echelon distribution schemes for e-commerce making a deep analysis of a French case study. Also relational aspects have been studied, more precisely in the context of collaboration in logistics partnerships. Newbourn (1997) defines the main principles a logistics partnership and the differences between other forms of inter-enterprise relationships. Lambert et al. (1996) propose a first model to analyze their feasibility from a management point of view. These works are mainly related to production and warehousing, and involve in general multiple participants.

To deal with the practical implications of multi-echelon transportation, socio-economic issues related to the acceptability and the human limits to the development of systemic management approaches are envisaged. However, only few works related to multi-echelon freight transportation with cross-docking can be found in literature. Beuthe and Kreutzberger (2001) analyze different multi-echelon schemes and estimate the changes on their cost functions. Simonot and Roure (2007) are interested to

transport networks constitution, objectives and organizational behavior, proposing a typology of networks for collaborative transportation. TL&Associés and .LET (2009) propose an analysis on 6 case studies presenting multi-echelon distribution systems to define the main leverages to change transportation demand. From a proposed list of leverages, it appears that transport management and modal split were the less used, because of several limitations related to the relations between the expeditionary stakeholders and the transportation carriers. Gonzalez-Feliu and Morana (2011) propose a case study for the press distribution, in order to study the limits to possible changes in their distribution schemes.

In conclusion, several works deal with multi-echelon transportation with cross-docking in a global point of view, but they are in general related to a discipline. We observe two many families of works: (1) combinatorial optimization methods, mainly related to computer science and applied mathematics, and (2) works from micro-economics, business, management and accounting, focusing on managerial an relationship aspects and do not present explicitly issues on transportation management and optimization. Therefore, these communities are seldom collaborating to provide multidisciplinary analysis and points of view. In a very applied research subject like multi-echelon transportation, these collaboration seems essential to deal with realistic and applicable methods and analysis. In order to deal with this question, we propose below an optimization analysis focusing on practical and applicability aspects (section 3), then a socio-economic feasibility study (section 4).

3. Optimization analysis

In this section we present the conceptual issues of transport cost optimization in multi-echelon systems as well as two analysis to show the potential of these approaches.

3.1. Issues for a single-transporter multi-echelon transport

Consider a transportation carrier that has to deliver a set of N_C destinations, called customers (Fisher, 1994). Each customer i has associated a demand q_i , i.e. a quantity of freight that has to be delivered. We suppose that the carrier has the infrastructures and vehicles to follow both single-echelon and two-echelon transportation strategies. In other words, the carrier has one depot and N_S intermediate

facilities where cross-docking operations can take place. These intermediate platforms are called satellites in our study, following the notation of Crainic et al. (2004). Moreover the company has two fleets of homogeneous vehicles, which number is respectively m_1 and m_2 . The first fleet of vehicles has a maximum capacity C^1 which is bigger than that of the second fleet, denoted C^2 . Therefore, we suppose that vehicles of the first fleet, i.e. those with bigger capacity, cannot access directly to the customers. This is the case of many cities, where in some central parts the streets are not large enough to allow these vehicles to pass. Each satellite k presents a capacity m_{sk} that corresponds to the maximum number of small vehicles that can be allocated to the satellite.

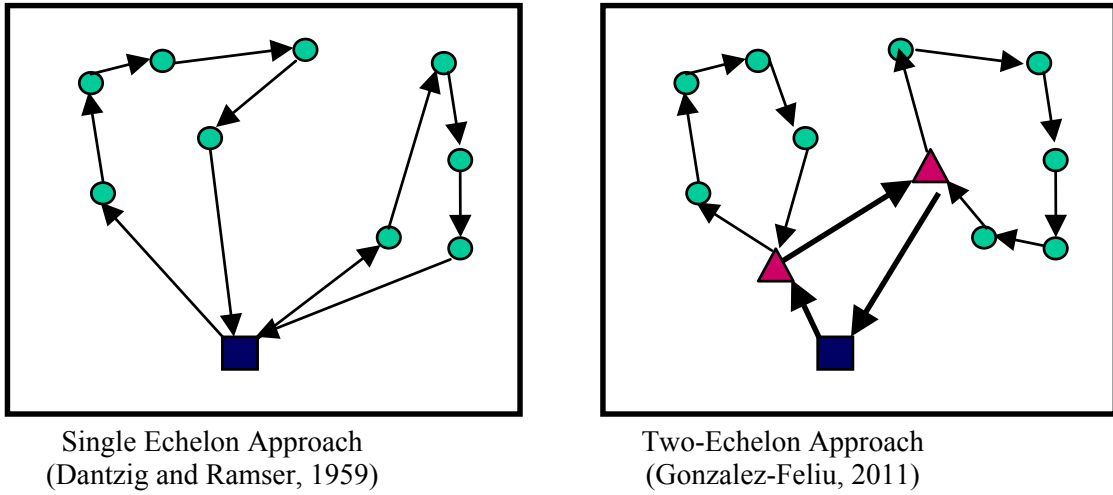


Figure 2 – Single-echelon and two-echelon vehicle routing schemes

Consider a graph G that represents the transportation system. The depot is included on a set V_0 , the set of satellite nodes is denoted by V_S , and the set of customers by V_C . Then we define each arc (i,j) as the link between node i and node j . We define the cost c_{ij} as the travel distance associated to arc (i,j) . We suppose that we have an undirected graph, i.e., the cost associated to arc (i,j) is the same as that of arc (j,i) . If the company wants to follow a single-echelon approach, we can define a cost optimization problem derived from classical vehicle routing (Fisher, 1994). In this approach, all routes start and finish at the depot and each customer is visited once. Moreover, each vehicle makes only one route (Toth and Vigo, 2002). We define two types of variables. First, the variable t_{ij} a binary variable that is equal to 1 if a vehicle goes from node i to node j , 0 otherwise. Then, the real variable Q_{ij} represents the quantity freight loaded in a vehicle passing through each arc. The model can be formulated as follows:

$$\min \sum_{i,j \in V_0 \cup V_C} c_{ij} t_{ij} \quad (1)$$

Subject to

$$\sum_{i \in V_C} t_{0i} \leq m_2 \quad (2)$$

$$\sum_{j \in V_C} t_{j0} = \sum_{i \in V_C} t_{0i} \quad (3)$$

$$\sum_{j \in V_C} t_{ij} \leq 1 \forall i \in V_S \cup V_C, i \neq j \quad (4)$$

$$\sum_{i \in V_S} Q_{ij} - \sum_{k \in V_S} Q_{ik} = \begin{cases} q_j & \text{if } j \text{ is not the depot} \\ \sum_{i \in V_C} -q_i & \text{if we consider the depot} \end{cases} \quad (5)$$

$$\forall j \in V_0 \cup V_C, k \neq i, k \neq j$$

$$Q_{ij} \leq C^2 \quad \forall i, j \in V_0 \cup V_C, i \neq j \quad (6)$$

$$t_{ij} \in \{0,1\}; \forall i \in V_0 \cup V_C; \forall j \in V_0 \cup V_C; i \neq j \quad (7)$$

$$Q_{ij} \in \mathfrak{R}; \forall i \in V_0 \cup V_C; \forall j \in V_0 \cup V_C, i \neq j \quad (8)$$

The objective function (1) is to minimize the total transportation cost, obtained by addition of the cost of each traveled arc of the network. The maximum number of vehicles is m_2 (2). Each route starts and finishes at the depot (3) and visits only one customer (4). Constraints (5) indicates that each customer's demand q_i is loaded at the depot and unloaded respectively at each customer's location. Moreover, the vehicle's load cannot exceed its capacity (6). Finally, expressions (7) and (8) show the nature of the variables, binary for t_{ij} and real for Q_{ij} .

If the carrier wants to use a transportation system with cross-docking, a two-echelon approach is needed. In this approach, two types of routes are defined. The 1st-echelon routes are made by the fleet of m_1 vehicles, called 1st-echelon vehicles. A 1st-echelon route starts and finishes on the depot, and visits the satellites. Note that satellites can be visited by more than one 1st-echelon route. Moreover, the carrier can decide to not use all the satellites. At the satellites, the freight is transshipped into the

2nd-echelon vehicles, those belonging to the other fleet. Each route made by these vehicles, called 2nd-echelon route, starts and finishes on a satellite, and visits one or more customers. Each customer is visited by only one 2nd-echelon vehicle.

The variables included in the model are the following. The variable x_{ij} is an integer variable that represents the number of 1st-echelon vehicles traveling through arc (i,j) . The variable y_{ij}^k is a binary variable that is equal to 1 if a 2nd-echelon route starting from satellite k travels through arc (i,j) , 0 otherwise. Moreover we define z_{kj} as a binary variable that is equal to 1 if the freight to be delivered to customer j is transshipped at satellite k , 0 otherwise. Finally we define a set of variables, split into two subsets, one for each echelon, represents the quantity freight loaded in a vehicle passing through each arc. This variable is real and can be noted as Q_{ij}^1 , Q_{ij}^{2k} respectively for each echelon, k representing the satellite where the 2nd-echelon route starts. The model can be written as follows:

$$\min \sum_{i,j \in V_0 \cup V_S} c_{ij} x_{ij} + \sum_{k \in V_S} \sum_{i,j \in V_S \cup V_C} c_{ij} y_{ij}^k \quad (1)$$

Subject to

$$\sum_{i \in V_S} x_{0i} \leq m_1 \quad (2)$$

$$\sum_{j \in V_S} x_{j0} = \sum_{i \in V_S} x_{0i} \quad (3)$$

$$\sum_{k \in V_S} \sum_{i,j \in V_C} y_{ij}^k \leq m_2 \quad (4)$$

$$\sum_{i,j \in V_C} y_{ji}^k = \sum_{i,j \in V_C} y_{ij}^k \quad \forall k \in V_S \quad (5)$$

$$\sum_{i \in V_S} Q_{ij}^1 - \sum_{k \in V_S} Q_{jk}^{2k} = \begin{cases} \sum_{h \in V_C} q_h z_{jh} & \text{if } j \text{ is not the depot} \\ \sum_{i \in V_C} -q_i & \text{if we consider the depot} \end{cases} \quad (6)$$

$$\forall j \in V_0 \cup V_S, k \neq i, k \neq j$$

$$Q_{ij}^1 \leq C^1 x_{ij} \quad \forall i, j \in V_S \cup V_0, i \neq j \quad (7)$$

$$\sum_{i \in V_c} Q_{ij}^{2k} - \sum_{l \in V_c} Q_{jl}^{2k} = \begin{cases} z_{kj} q_j & \text{if } j \text{ is not a satellite} \\ - \sum_{h \in V_c} q_h z_{jh} & \text{if we consider the satellite } j \end{cases} \quad (8)$$

$$\forall j \in V_S \cup V_C, \forall k \in V_S, l \neq i, k \neq j$$

$$Q_{ij}^{2k} \leq C^2 y_{ij}^k \quad \forall i, j \in V_S \cup V_0, \forall k \in V_S, i \neq j \quad (9)$$

$$\sum_{i \in V_S} Q_{i0}^1 = 0 \quad (10)$$

$$\sum_{i \in V_C} Q_{ik}^{2k} = 0 \quad \forall k \in V_S \quad (11)$$

$$y_{ij}^k \leq z_{kj} \quad \forall i, j \in V_S \cup V_C, \forall k \in V_S \quad (12)$$

$$y_{ij}^k \leq \sum_{h \in V_S \cup \{0\}} x_{hk} \quad \forall i \in V_S, \forall j \in V_C, \forall k \in V_S \quad (13)$$

$$\sum_{k \in V_S} z_{kj} = 1 \quad \forall j \in V_C \quad (14)$$

$$\sum_{i \in V_S \cup V_C} y_{ij}^k = z_{kj} \quad \forall i \in V_S, i \neq k \quad (15)$$

$$\sum_{j \in V_S \cup V_C} y_{ji}^k = z_{ki} \quad \forall i \in V_S, i \neq k \quad (16)$$

$$\sum_{i \in V_c} y_{ki}^k \leq m_s; \forall k \in V_S \quad (17)$$

$$x_{ij} = \{0,1\}; \forall i \in V_0 \cup V_S; \forall j \in V_0 \cup V_S \quad (18)$$

$$y_{ij}^k = \{0,1\}; \forall i \in V_S \cup V_C; \forall j \in V_S \cup V_C; \forall k \in V_S \quad (19)$$

$$z_{ki} = \{0,1\}; \forall i \in V_C; \forall k \in V_S \quad (20)$$

$$Q_{ij}^1 \in \mathfrak{R}; \forall i \in V_0 \cup V_S; \forall j \in V_0 \cup V_S \quad (21)$$

$$Q_{ij}^{2k} \in \mathfrak{R}; \forall i \in V_S \cup V_C; \forall j \in V_S \cup V_C; \forall k \in V_S \quad (22)$$

The objective function (1) seeks to minimize the overall transportation cost. The number of the routes in each echelon must not exceed the number of vehicles for that echelon, as imposed by constraints (2) and (4). Constraints (3) show, for that each 1st-echelon route begins and ends at the depot and impose the balance of vehicles entering and leaving each satellite. Constraints (5) force each 2nd-echelon route to begin and end to one satellite and the balance of vehicles entering and leaving each customer.

Constraints (6), (8), (10) and (11) ensure that each route starts and ends at the depot and a satellite, respectively for each echelon, and each node receives its corresponding demand. The vehicle capacity constraints are expressed by equations (7) and (9), respectively for each echelon. Constraints (12) and (13) ensure the connection between the two echelons.

Constraint (14) assigns each customer to one and only one satellite, while constraints (15) and (16) indicate that there is only one 2nd-echelon route passing through each customer. The limit on the satellite capacity is satisfied by constraints (17). Equations (18) to (22) are related to the nature of variables (real for flow variables and $\{0,1\}$ for arc and assignment variables).

In order to test the two-echelon model, we propose three sets of test instances, derived respectively from the instances denoted as E-n13-k4, E-n22-k4, E-n33-k4 and E-n51-k5, proposed by Christofides and Eilon (1969). The first set of instance is made by 66 small-sized instances with 1 depot, 2 satellites and 12 customers. The number of vehicles for the 1st-echelon is set to 2, while the number of 2nd-echelon vehicles in the same as that of E-n13-k4. The capacity of the 1st-level vehicles is 2.5 times the capacity of the 2nd-echelon vehicles. The capacity of the 2nd-level vehicles is equal to the capacity of the vehicles of the VRP instance. The other two sets of instances are obtained in a similar way from the instances E-n22-k4, E-n33-k4 and E-n51-k5. The second set derives directly from the instances of Christofides and Eilon (1969), that have a central depot. The third set proposes instances where the initial depot has been moved on an external point and the satellites are chosen among the peripheral customers near the new depot. Their characteristics are presented in Table 1:

Table 1 – Main Characteristics of Proposed Instances.

Set	Number of instances	N _s	N _c	m ₁	m ₂	C ₁	C ₂	Customer distribution
1	66	2	12	3	4	15000	6000	From Chistofides and Eilon E-n13-k4
2	6	2	21	3	4	15000	6000	From Chistofides and Eilon E-n22-k4
2	6	2	32	3	4	20000	8000	From Chistofides and Eilon E-n33-k4
2	6	2	50	3	5	400	160	From Chistofides and Eilon E-n51-k5
3	6	2	21	3	4	15000	6000	From Chistofides and Eilon E-n22-k4
3	6	2	32	3	4	20000	8000	From Chistofides and Eilon E-n33-k4
3	6	2	50	3	5	400	160	From Chistofides and Eilon E-n51-k5

We applied the proposed 2-echelon model to each set of instances by means of XPress 2006 solver (Dash Associates, 2006), giving a maximum computation time of 45 minutes. The proposed formulation is able to solve to optimality all instances up to 21 customers, as well as two having 32 customers and a peripheral depot. This means that Xpress solver proves that the best solution is the global optimum. The other instances are not solved to optimality, but several solutions are found in general in reasonable times, i.e. less than 20 minutes. We observe that only instances with 50 customers and a central depot are not well solved. For the other instances, the best solution. In the other cases, we reach in average a gap lower than 10% between the best solution and its best lower bound found with Xpress solver.

Table 2 – Main Results After Applying the Model on Small and Medium Instances

Set	Group of instances	N _s	N _c	Number of instances	Number of exact optima	Average 2E-CVRP solution	Average Best Bound	Average Gap
1	E-n13-k4-2s-c	2	12	66	66	278	278	0,00%
2	E-n21-k4-2s-c	2	20	6	6	411	411	0,00%
2	E-n33-k4-2s-c	2	32	6	0	771	695	9,85%
2	E-n51-k5-2s-c	2	50	6	0	617	349	43,51%
3	E-n21-k4-2s-p	2	20	6	6	411	411	0,00%
3	E-n32-k4-2s-p	2	32	6	2	710	666	6,24%
3	E-n51-k5-2s-p	2	50	6	0	526	500	4,87%

3.1.1. Accessibility analysis

In order to study the impacts of multi-echelon transportation with cross-docking with respect to one-echelon transportation systems, we propose a geographic analysis based on the notion of accessibility.

The notion of accessibility has been defined in literature in several ways. In our study, we will extend to freight transport the definition of Geurs and van Wee (2004). In this way we can define accessibility as the extent to which land-use and transport systems enable individuals to reach destinations by means of a transport mode. According to the authors, four categories of accessibility indicators can be defined.

The first category is that of infrastructure-based indicators, largely used in transport planning studies made by public authorities. These measures deal with service level related to a transport infrastructure, as for example the congestion level or the average travel speeds on a road network (Linneker and Spence, 1992; Erwing, 1993). The second is that of location-based measures, analyzing accessibility at physical locations, usually on a macroscopic perspective. The measures usually describe the level of accessibility to spatially distributed activities, and are largely used in urban planning and geographical studies. Two main groups of indicators can be distinguished in this category: distance based indicators and potential accessibility measures. The distance-based indicators (Ingram, 1971; Pirie, 1979), also called connectivity measures, represent the degree of which two locations are connected. Several distance measures can be defined, as for example the line distance between two points, other non-linear distance measures, the travel time or the transportation cost required to access a number of opportunities (Geurs and van Wee, 2004). The potential accessibility, also called gravity-based measures, estimate the accessibility of opportunities in zone i to all other zones. These measures take into account both the number of opportunities and the transportation costs to reach them (Stewart, 1947; Hansen, 1959; Ingram, 1971; Vickerman, 1974). This indicator can be generalized as follows:

$$A_i = \sum_j D_j \cdot f(c_{ij})$$

where A_i is the potential accessibility of a zone i , D_j are the opportunities at each destination zone j , c_{ij} the transportation cost between zone i and zone j and β the cost sensibility parameter.

The third category contains person-based measures, which define accessibility at the individual level (Burns, 1979). This type of measure is founded in the space–time geography of Hägerstrand (1970) and measures limitations on an individual's freedom of action in the environment (Miller, 1999;

Recker et al., 2001). The fourth one is related to utility-based measures, which derive from the main benefits that people derive from access to the spatially distributed activities. This type of measure has its origin in economic studies, and interprets accessibility as the outcome of a set of transportation choices. Two main types of measures are used: logsum indicators, which study the desirability of the full choice set (Ben-Akiva and Lerman, 1979), and doubly constraint entropy models (Martinez, 1995).

The proposed analysis will follow the point of view of a single transportation operator. In this context, personal indicators seem not adapted because carrier-oriented transportation planning often refers to facility location and fleet management. Moreover, in multi-echelon freight transportation systems the main cost optimization issues are related to total traveled distance, related to the geographic configuration of the transportation network. For these reasons, location-based indicators seem the most indicated to our study since they take into account the geographic context and can use both costs and opportunities as main variables.

However, a two-echelon transportation system is defined by two connected transportation schemes, each of them assigned to one echelon. For the first echelon, the freight is not pre-assigned to each intermediary facility. Although the capacity and other operational data of these facilities is available, the opportunities are extremely related to the second echelon. For this reason, we will define two accessibility indicators. We will start to define a gravity accessibility measure for the second echelon, derived from the general definition presented above. In our study, the opportunities are related to each customer's demand, i.e. a freight transportation trip is more attractive when a bigger quantity of freight has to be delivered to the customer's location. Moreover, the cost is defined as the travel distance between two zones, i.e., a customer is less accessible when the distance increases. The chosen cost function is an exponential gravity function to accentuate the role of increasing distances. This indicator has the following form:

$$A_k = \sum_{i \in V_c} D_k e^{-\beta c_{ki}}$$

In order to compare instances of different sizes and scales, we need a normalized accessibility indicator which value range is not depending neither on instance size nor on the distance scale. We propose to define this measure as follows:

$$A_k = \sum_{i \in V_c} \frac{q_i}{q_{\max}} e^{-\beta \frac{c_{ki} - c_{\min}}{c_{\max} - c_{\min}}}$$

where q_i is the demand of the customer i , q_{\max} the maximum demand overall for the customers, c_{ki} the transport cost between the satellite k and the customer i , c_{\min} and c_{\max} the minimum and maximum values of the second-echelon transport costs, respectively, and $\beta > 0$ a given parameter representing the travelling impedance (we have assumed $\beta = 0,1$ following practical considerations). Concerning transportation cost, we take into account the Euclidean distances.

To complement this accessibility indicator, we propose a second measure derived from average distance ratios. This indicator measures how longer is to deliver the customer passing through a satellite with respect to using a direct transportation path from the depot to the customer.

To distinguish both accessibilities, this second indicator will be denoted as *first-echelon distance ratio*, and is defined for each satellite k , as follows:

$$r_k = \frac{\sum_{i \in V_c} \frac{c_{0k} + c_{ki}}{c_{0i}}}{n_c}$$

In order to perform the accessibility analysis, we take into account the 80 instances solved to optimality representing a set of 2-echelon transportation schemes and compare their traveled distances to those of the corresponding single-echelon instances (Christofides and Eilon, 1965). We calculate the overall transportation cost for each instance then we compare the two-echelon ones with their respective single-echelon instances in order to observe if there is a gain or a loose in the total traveled distance. Moreover, we propose three ranges of second-echelon accessibility and first-echelon transportation cost ratio. The mean second-echelon accessibility is split into three sets:

- Low (L): mean accessibility in the interval $[A_{\min}, \{33\% \text{ of } [A_{\min}, A_{\max}]\}]$.

- Medium (**M**): mean accessibility in the interval $[\{33\% \text{ of } [A_{min}, A_{max}]\}, \{67\% \text{ of } [A_{min}, A_{max}]\}]$.
- High (**H**): mean accessibility in the interval $[\{33\% \text{ of } [A_{min}, A_{max}]\}, A_{max}]$.

where $A_{min} = \min_k \{A_k\}$ and $A_{max} = \max_k \{A_k\}$.

Analogous to accessibility, first-echelon transport cost ratios have been categorized into three sets:

- Low (**L**): mean transport cost ratio of the satellites in the interval $[r_{min}, \{50\% \text{ of } [r_{min}, r_{max}]\}]$.
- Medium (**M**): mean transport cost ratio of the satellites in the interval $[\{50\% \text{ of } [r_{min}, r_{max}]\}, \{67\% \text{ of } [r_{min}, r_{max}]\}]$.
- High (**H**): mean transportation cost of the satellites in the interval $[\{67\% \text{ of } [r_{min}, r_{max}]\}, r_{max}]$.

We report the synthesis of the results as follows. Table 3 includes two values in each cell. The first value is the number of cases where the total transportation cost of the 2nd-echelon distribution schema is lower than that of its corresponding 1st-echelon strategy. The second value is the number of cases where the opposite happens. Table 4 shows the average cost gain or loss with respect to the one-echelon approach. We observe that multi-echelon systems can present some advantages in terms of transportation cost as shown below and, although the number of customers is small, the analysis is interesting because the comparison takes place between exact optimums.

Table 3 – Synthesis of the Optimization Analysis on Small Instances

Mean 2nd- echelon accessibility	High	10/1	9/2	0/6
	Medium	12/3	4/2	1/4
	Low	11/5	3/6	0/1
		Low	Medium	High
Mean 1st-echelon transport cost ratio				

Table 4 – Average Percent Gain-Loss with Respect to the Single-Echelon Optimum

Mean 2nd- echelon accessibility	High	-23%	-7%	14%
	Medium	-20%	-11%	14%
	Low	-11%	-8%	6%
		Low	Medium	High
Mean 1st-echelon transport cost ratio				

Multi-echelon distribution leads to a cost reduction in 50 of the 80 instances (almost 63% of the cases), while the decreasing/increasing of the costs is on the average between -25% and $+25\%$ of the transport cost of a single-echelon system. The cost gain is about 11%, but these reductions are not homogeneously distributed. When the 1st-echelon cost ratio is high (i.e., when passing through the satellite implies a big overall cost increase), it is logic that 2-echelon transportation systems are not useful: almost all the instances in this group (11/12) result on a cost loss and the 2nd-echelon accessibility has a little influence with respect to cost ratio. Indeed, we observe an average cost increase of near 13,5% with a standard deviation of 8%, with similar results for medium and high accessibility. For medium cost ratios, we observe that 60% of the cases result on transportation cost gains (16 out of 26 cases), with better gains for medium accessibility instances. This can be explained by the fact that most instances with high accessibility in this group present higher cost ratios than those with medium accessibility. Finally, if we observe the group of low cost ratio instances we observe that the accessibility has a higher influence than in the other groups. In this group, 78% of the cases (33 out of 42) result on cost savings with respect to their corresponding single-echelon approach, with an average gain of 17%. In this group, low-accessibility instances result on an average gain of 11%, medium-accessibility cases on 20% and those with high accessibility on 23%. The number of instances where gains are seen increase also for medium and high accessibilities.

From this analysis, we can state that the proposed indicators can be used to study the potential of 2-echelon transportation systems with cross-docking. In this analysis, only transportation cost, directly related tot travelling distances, has been taking into account in order to produce a homogeneous comparison between single-echelon and two-echelon transportation schemes. However, no investment costs have been taken into account, more precisely those related to the financing of infrastructures and vehicles needed in 2-echelon schemes. Therefore, issues concerning investments and financing will be taken into account in the socioeconomic analysis further presented.

3.2. Comparison of single-user and collaborative multi-echelon systems

In order to make a comparison of multi-echelon strategies, we propose a scenario analysis using data adapted from the instances proposed by Fisher (1994) for the Capacitated Vehicle Routing Problem that can be used to reproduce hypothetical transport plans. Each instance is assimilated to a transportation company. Moreover, we add to each instances complementary information to transform each transportation system on a potential two-echelon transportation system. Furthermore, we have adapted these instances to simulate the demand of three transportation companies belonging to the same field. The proposed instances can be resumed on Table 5:

Table 5 – Main Characteristics of Each Carrier (Adapted from Fisher, 1995)

Number	Original Instance	Number of customers	n_s	n_c	m_1	m_2	C_1	C_2
1	F-n72-k4	71	2	71	2	6	7800	3000
2	F-n45-k4	44	2	44	2	6	6500	2500
3	F-n137-k7	136	3	136	3	10	6500	2500

From these instances, we can define four scenarios. The first represents the case where each company has a single-echelon transportation system. To estimate the transport costs, we use the simulation method on a CVRP for each company and we calculate the overall transport cost resulting as the sum of each company's cost. In the second scenario, each carrier develops its own two-echelon distribution strategies. The third presents a first form of collaboration, that of sharing the cross-docking platforms. The fourth supposes a complete collaboration among partners, which share both vehicles and facilities. To perform a comparative analysis we propose a simulation method to estimate the overall routes corresponding to each scenario. Because we want to represent realistic situations, and also solve the optimization problem in an approximate but quick way, we propose a two-step algorithm. First, the customers' demands are grouped on clusters, then, for each cluster, a route is built using a modified greedy algorithm (Jacobsen and Madsen, 1980). The gap between the optimal solution and the algorithm's costs remains similar for each simulation. In this context, the comparison between the scenarios is homogeneous.

The algorithm works as follows: given a set of customers, a set of satellites and a set of depots, the algorithm has to construct the overall two-echelon vehicle routing schema. The first phase is clustering, where the customers will be assigned to each 2nd-echelon vehicle that will be also assigned

to a satellite. To do this we propose an algorithm derived from Forgy and Random Partition method proposed by Hamerly and Elkan (2002). To initialize this algorithm, we randomly choose m_2 observations from the data set (i.e. a number of customers equal to the number of 2nd-echelon vehicles). Each customer becomes the centroid of a cluster. Then, each customer is assigned to a cluster using a k-means algorithm. This algorithm is an iterative procedure that inserts each customer to a cluster in order to minimize the mean distance among customers of each cluster. In our case the mean distance to minimize has been chosen to be the Euclidean distance between each customer and the cluster's centroid. Each cluster will contain customers which overall demand do not exceed the capacity of the 2nd-echelon vehicle to which the cluster is associated. In order to take into account the two-echelon nature of the problem, once the clusters are defined, each of them is assigned to a satellite using the same principle (see 3).

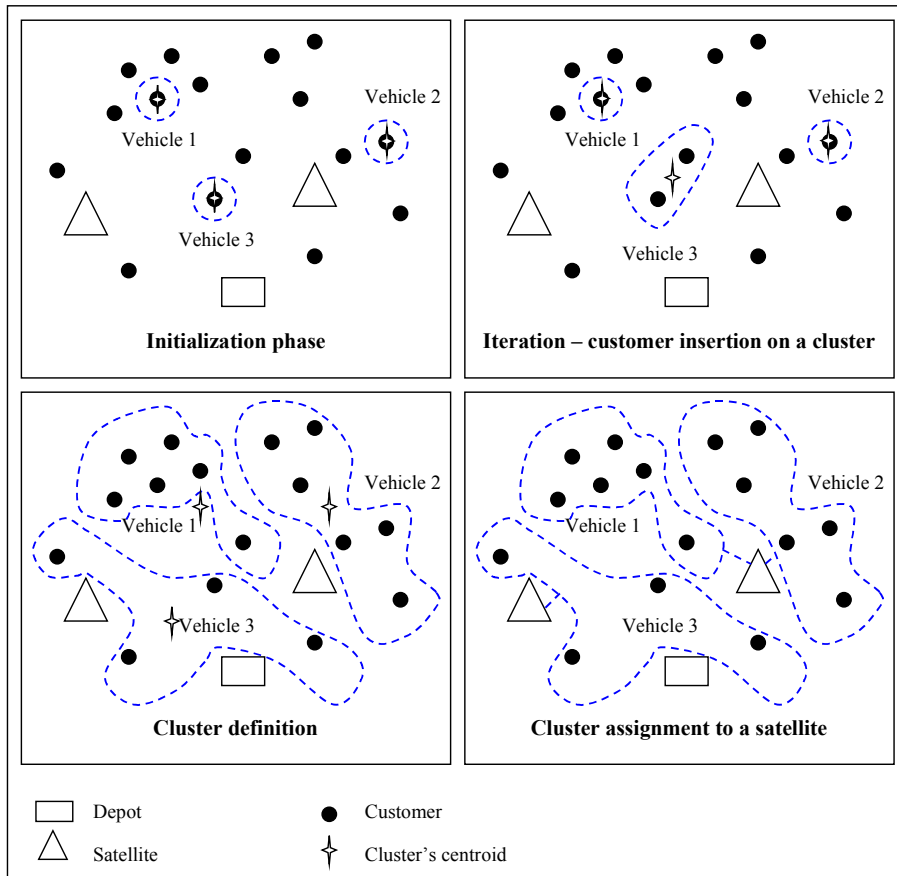


Figure 3 – An example of the Clustering Phase

The second phase is route construction. Given the satellite clusters defined in the first phase, a semi-greedy algorithm, derived from the works of Hart and Shogan (1987), is proposed. In the initialization phase of the algorithm each customer is related to a satellite as following the results of the clustering phase. Then, for each satellite, we take into account a maximum number of routes equal to the number of clusters assigned to it in the clustering phase. Routes are generated following an iterative procedure that adds each customer to a route in the following manner. Given an iteration and an uncompleted route, a list of candidates is defined by taking the n closest customers to the last point of the route (see 4). This is made by defining a distance threshold δ . Customers which distance to the last point of the route is less than δ are included into this list, that will be called Restricted Candidate List (RCL). Then, the customer inserted on the route is chosen at random from the RCL customers. This kind of greedy randomized construction method is also known as a semi-greedy heuristic (Resende and Ribeiro, 2003). Finally, the first echelon routes are build following the same principle, knowing the load that will transit on each satellite from the second-echelon routes. Since the number of intermediary facilities is small, a combinatorial procedure is included to exchange the satellite of each route in order to improve the global solution. The proposed algorithm solves instances of more than 200 destinations and 5 satellites in less than 1 second.

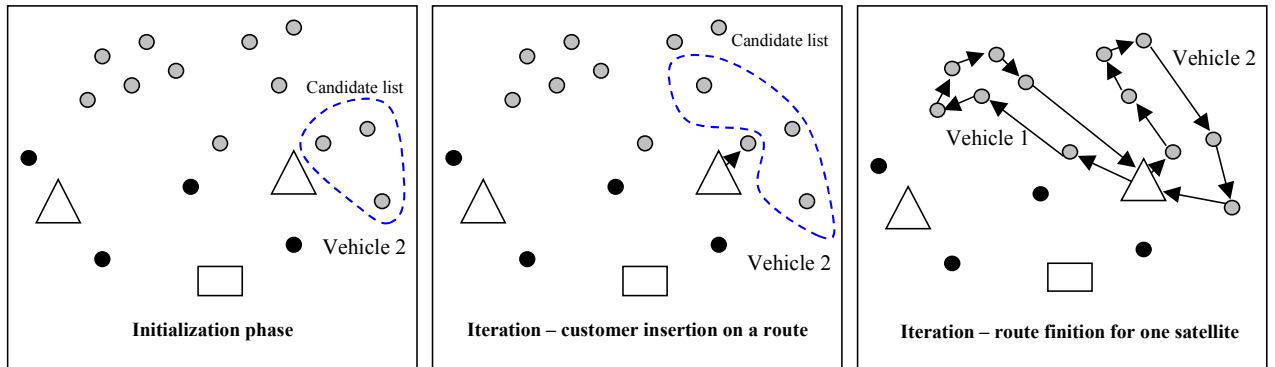


Figure 4 – Schema of the Semi-Greedy Algorithm for the 2nd-Echelon Routes

In order to adapt the algorithm to a single-echelon system, this scheme is represented by a two-echelon system with one satellite which distance to the depot is equal to zero. The different scenarios have been tested using our simulation approach programmed in Python. In this analysis we identify as the main cost sources the traveled distances, the number of open cross-docking platforms and the number of vehicles used. We will not use a generalized cost function but will analyze these three variables and

deduce the main implications, taking into account that each component has a different influence for each carrier.

Table 6 – Scenario Simulation Results

	1 st -echelon vehicles	2 nd -echelon vehicles	Used satellites	1 st -echelon vehicle variation	2 nd -echelon vehicle variation	Distance variation
0	0	15	0	-	-	-
1	7	22	7	+7	+7	-5%
2	7	21	7	+7	+6	-10%
3	5	14	4	+7	-1	-22%

We observe that all scenarios result on distance gains, but imply a higher number of vehicles. Scenario 1 presents small gains (about 5% on the total travel distance) but mobilizes a higher number of vehicles. In this scenario, each carrier needs to almost double their number of vehicles (all available vehicles are used). This is due to the algorithm hypothesis and assumptions, that assign vehicles to each satellite and avoids using the same vehicle for more than one route. The number of open platforms is 7, i.e. each carrier opens all the satellites they have, which implies to provide a number of employees on each site to perform the different operations related to consolidation and transshipment. A similar situation is observed in scenario 2. Indeed, if only platforms are shared the transportation costs can only be improved by using more platforms, which is not the best for the number of satellites and vehicles used. Indeed, the number of open satellites remains the same but they are used by all three carriers. A small reduction on the number of 2nd-echelon vehicles is used, because one carrier can, by using a satellite not belonging to it, group a set of customers to gain one vehicle. The overall transportation costs, i.e. the traveled distances, are reduced about 10% with respect to scenario 0, i.e., one-echelon schemes for each company. Finally, scenario 3, i.e. collaboration among all the carriers to share also vehicles, leads to a reduction of about 22% of the total traveled distances and a better usage of vehicles. Indeed, in this scenario 19 vehicles are used (5 for the first and 14 for the second echelon, which is the best that it can be performed taken into account the capacity constraints. Note that in these simulations, we have taken into account that one route is performed by only one vehicle. The cost gains related to the kilometers traveled by the vehicles remain however small if we consider that other costs mostly related to consolidation and vehicle driving are added but have not been considered in

this study. To complete the study, a socioeconomic analysis on major limitations to transport sharing and collaboration is proposed in next section.

4. Socioeconomic analysis

As we have seen from simulation, multi-echelon transport can be an interesting approach to reduce the transport cost. However, the only transport cost gains do not ensure the success of these schemes. Indeed, they are part of a socio-economic context. In order to study this context, and more precisely the limitations to multi-echelon transportation with cross-docking, we propose a quick study on 20 experience's feedback cases.

The data collection methodology for the experience's feedback analysis has been carried out in the following way. First, the existing literature on the subject has been explored (see section 2). Moreover, several professional documents containing experience's feedbacks has also been analyzed. We have identified 25 cases as well as a key interlocutor for each of them. Then, a face-to-face semi-directive interview has been made to each interlocutor following the method described in TL&Associés and LET (2009). Moreover, the missing information has been completed by phone directive questions.

Each interview is organized in three parts. First, a directive questionnaire that identifies the main logistics schemes and flows of the enterprise is filled in. In many cases, the questionnaire was sent before the interview took place, in order to decrease the interview's time with both quantitative and qualitative data. The second contains a set of semi-directive questions about how the enterprise should change their logistics schemes in relation to different external factors. The third is a more open phase that consists on making the interlocutor define the main advantages and disadvantages of managing multi-echelon transportation systems with cross-docking. More precisely, it is asked to define a list of factors that help or oppose multi-echelon transportation schemes. For confidentiality reasons, the enterprises' identities are kept anonymous. The 25 interviews have been made to different types of stakeholders: 6 grocery distribution companies; 4 automotive and spare part industry companies, 3 press distribution companies, 3 urban consolidation centers, 4 parcel and postal distribution companies and 5 transport operators. Except urban consolidation centers, the interviewed stakeholders operate at continental (Europe, North America or East Asia) or world scales.

The questions in the interview guides are developed to introduce the different socio-economic and legislative factors related to multi-echelon transportation with cross-docking. The 25 cases are then analyzed and synthesized in order to complete the model. More precisely, three types of factors derived from the model are identified in each interview: the motivators, the accelerators and the limitations. Then, there are synthesized in order to generalize the findings of Lambert (2008) and Gonzalez-Feliu and Morana (2011) to multi-echelon transportation with cross-docking, and resulted on the following chart (Figure 5):

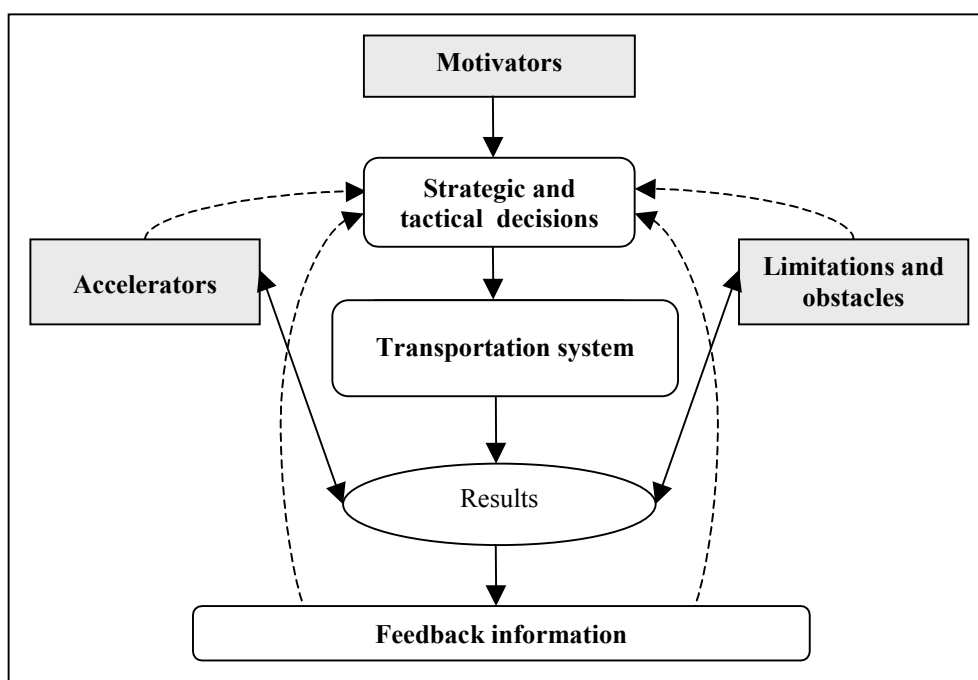


Figure 5– Conceptual Model for A Socio-Economic Analysis in Multi-Echelon Freight Distribution Planning and System Design

The motivators are the factors that incite the development of a transportation system with cross-docking. These factors are defined from the socio-economic and legislative context of the practices. More exactly, we can distinguish the following groups of motivators. First we can distinguish the *economic, environmental and value motivators*, defined as the factors related to economic efficiency, to prestige of the partners and to image. Sustainable performance is an important element to include in this category (Gonzalez-Feliu and Morana, 2011). Then we can highlight the legislation and jurisprudence aspects of transport collaboration, known as *legislative motivators*. Nowadays, the most

important aspects in this category are the different local laws that help the development of multi-echelon transportation systems in urban and regional freight transportation (Dablanc et al., 2011). The *relation motivators* are closely related to habits and inter-personal relations. When actors have already collaborated, because of common interests or because they belong to the same supply chain, so they are complementary, transportation sharing is more naturally taken into account than in cases where those conditions are not met. Moreover, non-concurrent or complementary enterprises are more concerned to these types of approaches in absence of legislative or financial motivators. Last, but not least, we find the *financial motivators*. They are related to subventions and financial help that can come from public, private or mixed entities. Several approaches have emerged from research and innovation projects financed (totally or partially) by public entities.

The facilitators are the conditions and situations that have a positive impact on the daily operations of a multi-echelon transportation schema. They are similar to those of collaboration and logistics partnerships (Lambert, 2008). These factors are not only related to the logistics organization but also to the evolution of the strategic planning relations between partners. A history of relations between two actors can facilitate a durable partnership. The boundary between the motivators and the facilitators is not always clear. However, we can distinguish these two categories by the fact that the motivators have an impact on the strategic decisions before the project is operative, and the facilitators have impacts which are observed at the operational level.

Closely related to the facilitators, the limitations and obstacles are those factors that can become an impediment to the successful development of strategies concerning multi-echelon transportation with cross-docking. and in preceding studies they have not been defined explicitly. These factors have been less studied. For this reason, we will focus on them in our analysis. From the experiences' feedbacks, we have identified several types of limitations and obstacles, which can be synthesized as follows:

First, we can find the *commercial strategies*. Each enterprise has its own commercial interests, which are not the same for loaders than for transport operators. If they are not a major source of conflicts among producers, retailers and logistics operators, they can become an important handicap for the transport operators. In fact, aggressive strategies and disregard of the transport plans to advantage

“friends” or customers have been identified by many transport operators as a brake to the development of collaborative multi-echelon networks.

Another important element is that of the *financial aspects* related to the implementation of a multi-echelon system, more precisely investment costs for the construction or adaptation of cross-docking platforms, depots or other infrastructures. Another source of disagreement is usually related to the “ownership” of them (or the management issues related to them) once they are operative.

Also the *logistics strategies* of each stakeholder, as well as the potential or real changes that a multi-echelon system organization could introduce, are a source of obstacles to their development. The physical and organizational conditions for freight compatibility, like dimensions, freight, type of packaging, loading unit and loading operations main characteristics are important, and they are not only related to legislation but also to organizational, equipment and habit. Another factor is the acceptability of the organizational changes, which also has to be taken into account when defining the main characteristics of the multi-echelon system, and they can lead to dysfunctions, delays or employees’ strikes and complaints that can impact the image and reputation of the system.

Two other important elements are *responsibility transfer* and *confidentiality*. The main transactions in freight transportation are regulated by several commercial contracts. However, the sub-contracting is not always well defined (Dablanc et al., 2010). Moreover, not all transport operators agree to let subcontractors make the last miles if the responsibility issues are not well defined. In case of conflicts, the responsibility transfer clause of the contract plays an important role because it can define the physical and the moral responsible(s) of the product’s loss or damage, and determine who has to pay for them. Moreover, confidentiality can become an obstacle to multi-echelon systems when two competing actors decide to collaborate to reduce their transport costs. Since information is the base of good collaboration, if one or more partners manage confidential information that they do not want to share for competitive reasons, the efficiency of the multi-echelon approach can decrease considerably. These issues are seen in most of the initiatives involving competing enterprises that do not have the support of public entities.

Moreover, other factors have to be explored. For example, the transport cost optimization is seen by the loaders as a competence of the transport operator. Moreover, in multi-echelon systems, several operators are participating, so a coordinated optimization is not easy to carry away.

5. Conclusion

In this paper we have presented a multidisciplinary analysis to study multi-echelon transport with cross-docking using both engineering and social sciences approaches. A mathematical model for overall transportation cost optimization has been presented and discussed. Moreover, two optimization analyses have been undertaken to study the potential of these systems, as well as the main limit. The first analysis, based on the notion of accessibility, shows that the physical and geographical characteristics of the network have an important impact on the development of transportation systems with cross-docking: such systems are useful if they allow to group the delivery points in order to use small vehicles to make short distances but they lose interest if in order to make these groups of deliveries the distances to reach the cross-docking platform are too high (it is important to well reduce the 2nd-echelon distances while containing the 1st-echelon ones). This statement is issued from the analysis using an indicator that relates both distances, called transportation cost ratio, which is a distance accessibility indicator. The second analysis explores the possibility of collaboration between transport carriers in order to optimize the vehicle loads. This analysis leads to two main conclusions. The first is that only by sharing the vehicles a significant cost reduction can be obtained, but other costs will appear, mainly related to the introduction of new vehicles and the usage of cross-docking facilities. This leads to the second conclusion, that can be enounced as the following statement: it is important to have enough freight to put on vehicles feeding the satellites, in order to better organize the distribution operations. In this perspective, collaboration seems a good way to increase the vehicles' loads, as seen in the second optimization study. To complete these analysis, a socio-economic study based on 25 experience's feedback cases have been undertaken. Several factors that can be considered incentives and limits to multi-echelon transportation with cross-docking have been identified. These factors are in both cases related to commercial strategies, financing, organization and legislation. Moreover, habits confidentiality and responsibility are also important obstacles to the

development of multi-echelon transportation systems with cross-docking. Since transport is used by humans, the social aspects of human interactions are important and can be its keys of success. Finally, we have to note that not all the drivers follow written instructions in transport plans. For these reasons, optimization methods are useful but have to meet the operational needs and limits, most of them related to habitude, which is difficult to change.

In conclusion, multi-echelon transport has a big potential and can be well accepted by practitioners and public authorities, but the structural changes have to be implemented in a medium term perspective, after identifying and analyzing the potential obstacles to the development of a project in order to ensure its continuity at an economic point of view. Finally, we can propose some future developments that can be done in two complementary directions: One is to provide more realistic simulation tools, by adding a cost function that takes into account not only traveled distances but other costs related to vehicle usage, crew scheduling, platform management and maintenance issues, among others. The other direction is that of including qualitative variables to the simulation approaches in order to develop integrated decision support systems to help planners and practitioners in their strategic or tactical decisions related to multi-echelon transportation with cross-docking. In this sense, the qualitative analysis would be extended and generalized to provide a qualitative modeling framework in order to include factors such as risk and acceptability into the simulation framework.

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Jesus Gonzalez-Feliu is a Post-Doctoral Researcher at the French National Center of Scientific Research (CNRS), and member of the Laboratoire d'Economie des Transports (LET, Laboratory of Transport Economics). He obtained his Civil Engineering Master's degree in 2003 at INSA Lyon (France) and passed his Ph.D. in operations research in 2008 at Politecnico di Torino (Italy). His Ph.D. thesis deals with urban freight distribution solutions and two-echelon vehicle routing problems. His research interests include city logistics planning and policy, freight demand modeling, decision support systems, vehicle routing optimization, sustainable supply chain management and collaborative transportation.