# Two-echelon freight transport optimisation: unifying concepts via a systematic review

Jesus Gonzalez-Feliu

# TWO-ECHELON FREIGHT TRANSPORT OPTIMISATION: UNIFYING CONCEPTS VIA A SYSTEMATIC REVIEW

**Jesus Gonzalez-Feliu. Laboratoire d'Economie des Transports. France**

**Abstract:** Multi-echelon distribution schemes are one of the most common strategies adopted by the transport companies in an aim of cost reduction, but their identification in scientific literature is not always easy due to a lack of unification. This paper presents the main concepts of two-echelon distribution via a systematic review, in the specific a meta-narrative analysis, in order to identify and unify the main concepts, issues and methods that can be helpful for scientists and transport practitioners. The problem of system cost optimisation in two-echelon freight transport systems is defined. Moreover, the main variants are synthetically presented and discussed. Finally, future research directions are proposed.

**Keywords:** location-routing problems; multi-echelon distribution; cross-docking; combinatorial optimisation; systematic review.

## 1. Introduction

Freight transport is an important component of supply chain management as it represents about 15% of the total costs of a product (Toth and Vigo, 2002, p. 5). In recent years companies have changed their inventory and distribution strategies for better adapting them to the changing demand, which has highlighted the importance of freight transport management. Moreover, the new advances in technology have been a positive factor for the development of new markets and new consumer needs, leading to the development of multi-echelon transport strategies. These strategies are part of complex supply chains (Brewer et al., 2001, pp. 1-2) that take into account many processes where transport management is seldom one of the main priorities. However, in the last years, the possibility to integrate route optimisation to production and inventory management has led to several findings in supply chain management research. These works are not easy to identify because the notation and definitions proposed by them do not follow the same patterns.

This paper aims to unify the concepts of multi-echelon freight transport using the meta-narrative analysis method proposed by Greenhalgh et al. (2005), very popular in healthcare research. We apply this method to operations research and management science issues, to identify and unify the vocabulary and notation on multi-echelon transport systems. First, the main motivations as well as the meta-narrative method are described in section 2. After that, the main findings of the analysis are presented. In section 3, the main meta-narratives identified are presented. Section 4 present the main concepts of two-echelon transport cost optimisation, in order to unify them. Section 5 proposes a first classification of cost optimisation problems in multi-echelon as well as an analysis on the main optimisation methods to these problems. Finally, the main research directions on this field are presented.

## 2. Motivation and methodology

One of the first aspects which takes place when relating freight transport to the outbound supply chain is the definition of one or more shipping strategies. The various strategies in practice can be related to:

- **Vehicle usage:** In some road transport strategies, vehicles are loaded to capacity. This policy is known as Full Truck Load (FTL). Instead, in other real applications, like in city logistics, most of the vehicles are not full-loaded, so the applied policy is known as Less-than-Truck Load (LTL). In this paper, we focus on LTL transport.

- **Hierarchical configuration:** This aspect can be defined using two groups of strategies (direct shipping and multi-echelon distribution).

Focusing on the way the freight goes to the final destination, i.e. the hierarchical configuration of the transport system, three predominant shipping strategies can be found in outbound logistics (Gonzalez-Feliu, 2008):

- **Direct shipping** consists in delivering freight directly from the origin to the destination.

- **Multi-echelon distribution with warehousing** is the technical name given to systems for products made by one or more factories, a set of warehouses, and the final destination of freight. Freight requests are made to warehouses, which have a stock of freight. These warehouses order freight in big quantities from factories.

- **Multi-echelon transport with cross-docking** differs from the warehousing strategy in the fact that cross-docking platforms do not have the possibility to stock, but allow the consolidation and transhipment operations, and the orders are made directly to the origin of the freight, which is in general a factory or a warehouse.

All these concepts seem well established but we observe several divergences in scientific literature. More precisely, the concepts related to multi-echelon logistics are well defined but we observe a lack concerning multi-echelon transport and cost optimisation issues that take into account the whole transport system and not only a part of it. In order to fill this lack, we propose to use a systematic review approach to identify the main issues concerning this field, mainly related to three questions:

1. How can a multi-echelon transport system be defined and which are the relations to the correspondent supply chains?

2. Can a unified general mathematical model be deduced from the main findings shown in scientific literature?

3. Which are the main approaches in operations research for cost optimisation of multi-echelon transport systems?

In order to answer to these questions, we propose to follow the meta-narrative method developed by Greenhalgh et al. (2005) as a way of systematically making sense of complex, heterogeneous, and conflicting bodies of literature. Because this complexity, heterogeneity and divergences can be found in the discontinuous literature of multi-echelon transport cost optimisation, we propose to adapt the meta-narrative method to the operations management field and more precisely to multi-echelon transport systems.

The essential technique of this method is based on an interpretative synthesis; i.e. in reading and rereading primary sources, using narrative reviews to summarise their key methods and findings in order to unify and synthesise the answers to the research questions presented above. According to Greenhalgh et al. (2005), a meta-narrative embraces a shared set of concepts, theories and preferred methods. The meta-narrative is sited within a particular scientific discipline and should to be regarded not as the unified voice of a community of scholars but as the unfolding of what they are currently discussing about. Indeed, researchers tend to cite one another's work, either to agree with or to contest it. Moreover, they attend the same conferences, publish in the same journals, and accept broadly similar criteria for judging validity and rigor.

The basic method can be found in Greenhalgh et al. (2005). In order to adapt it to operations research, which is a quantitative, applied mathematics field, we propose a small variation that is resumed in Figure 1. The framework we propose has as main goal to identify and analyse a set of meta-narratives that will be able to define and unify multi-echelon transport cost optimisation. More precisely, the method works as follows:

1. **Informal search phase**. With a view to identify a first set of meta-narratives, the main actions were exploratory (mainly browsing and asking colleagues), in order to find a first set of keywords. Then, using snowballing techniques (i.e. searching references of references and using citation-tracking databases), we were able to identify key sources. After that, seminal sources were identified by asking what were cited as key original and scholarly contributions by other researchers in the same field.

2. **Preliminary mapping phase**. From these sources, we extracted the concepts, methodological schemes that formed the criteria for rigor in each meta-narrative. Then, a first set of meta-narratives was defined.

3. **Formal search, clustering and appraisal iterative phases**. From the first set of meta-narratives, we implemented a formal search framework in order to identify (using techniques such as reference analysis, citation tracking or browsing techniques on selected and specific databases). Then, the papers found are analysed and appraised in order to select only those that can be included on at least one meta-narrative.

4. **Synthesis phase**. After several iterations (when no more works related to the chosen field, i.e., multi-echelon freight transport cost optimisation, are found), a synthesis of the chosen works is made. The most used keywords are identified and a literature refinement leads to the definition of the final set of meta-narratives.

5. **Writing up phase**. Finally, we can write a complete report that will set all the meta-narratives and references, in order to make a detailed documentary base for our analysis.

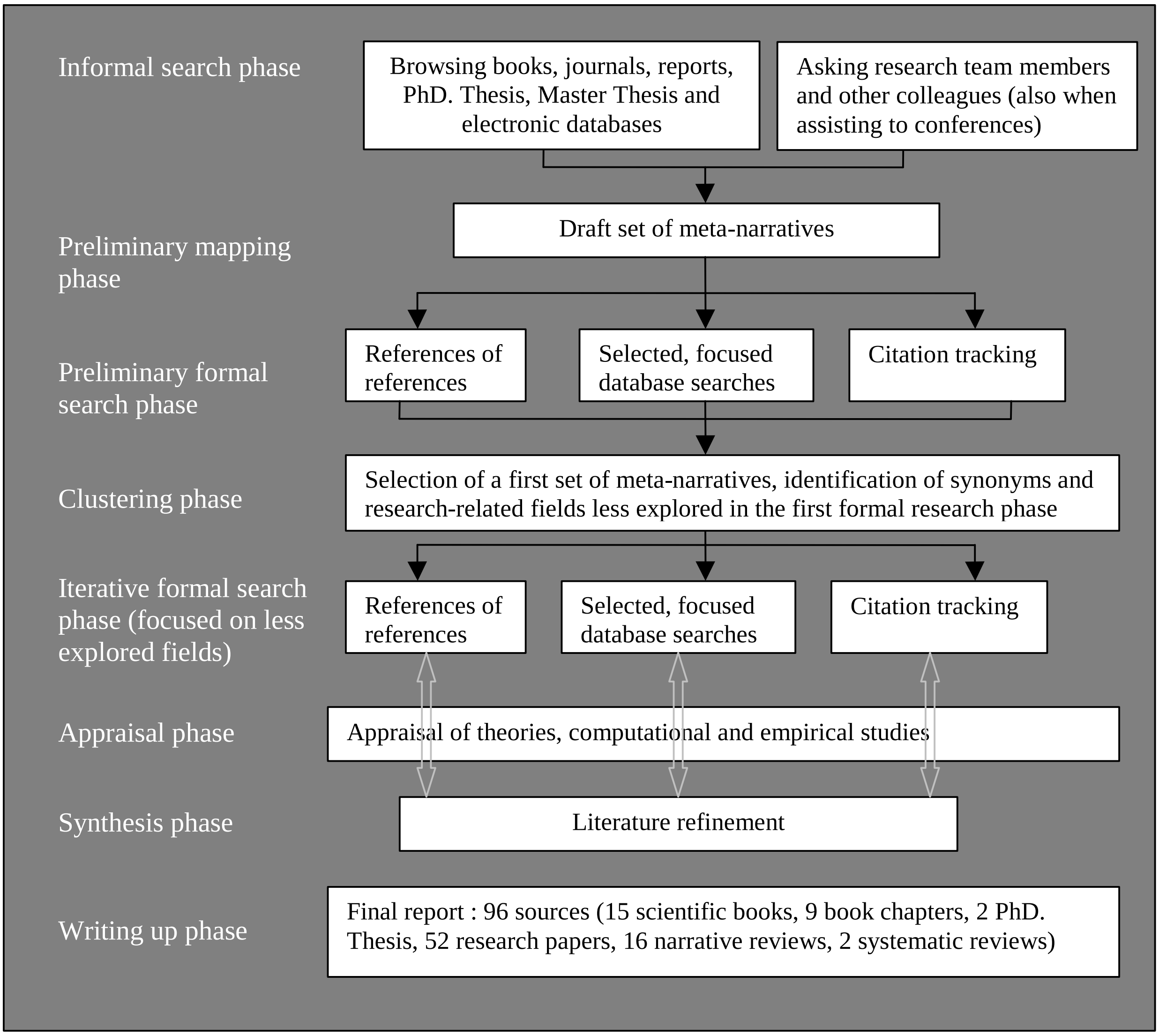


**Figure 1.** Summary of phases in the Meta-narrative method (adapted from Greenhalgh et al., 2009)

Systematic reviews, and more specifically meta-narrative analysis techniques are usually applied to empirical works. In our case, we deal with theoretical, modelling and computational studies, but our goal is similar as that of other systematic review: to identify and unify concepts on a field were only incomplete synthesis have been made. To straighten the method, we gave great weight to studies that had been flagged as "high quality" by other scholars in combinatorial optimisation, such as Min et al. (2002), Toth and Vigo (2002), Nagy and Sahli (2007) or Golden et al. (2008). As stated by Greenhalgh et al. (2005), the meta-narrative method is iterative and can sometimes lead to several false steps in the classification scheme and uncertainty about the quality and relevance of papers in traditions unfamiliar to us. The advantage of applying the method to the restricted field of multi-echelon transport management is that the number of total references is smaller than in other fields such as inventory management or demand forecasting. In most but not all cases we reached a high degree of agreement as the different meta-narratives took shape.

## 3. Main findings

After examining and selecting pertinent sources, we classified them in order to define the main meta-narratives. After a comparative analysis of these works, we have found 5 meta-narratives, which are detailed as follows:

*Nature of multi-echelon transport and differences with multi-echelon approaches of supply chain management*

The main difficulty of this study has been to identify the works dealing with multi-echelon transport, because the term defining this type of systems is not generalised and unified. We found several equivalent terms, as shown in Table 1. In some works, the multi-echelon nature of the transport system was indirectly taken into account but the transport systems were not defined using the concept of multi-echelon or a synonym. We observe that the most popular keywords are *echelon* and *transhipment*. However, the notion of echelon can be confusing if not well-defined. For this reason we propose then to precise this concept. In a supply chain, an echelon can be defined as the elementary organisation unit of this chain. This means that a supply chain, which results from a complex aggregation of operations, can be divided into various sets of homogeneous operations, mainly related to raw material collection, production, assembling, warehousing and transport. With this definition freight transport belongs to a separate echelon than inventorying or production, since their nature and management issues are different. So, a multi-echelon transport system is composed of at least two transport echelons. In other words, multi-echelon transport systems are multi-echelon logistics systems involving at least two transport schemes and cross-docking operations.

**Table 1.** Main keywords retained in the meta-narrative analysis

| | Keyword | Pertinent papers | Non pertinent papers |
|---|---|---|---|
| Multilevel nature of the transport system | Echelon | 31 | 46 |
| | Stage | 9 | 27 |
| | Level | 8 | 12 |
| | Tire | 3 | 0 |
| Relation between levels | Cross-docking | 8 | 15 |
| | Transhipment | 15 | 4 |
| | Synchronisation | 6 | 2 |
| | Truck-and-trailer | 14 | 0 |
| | Road-train | 5 | 0 |

*The role of intermediary facilities : multi-echelon transport with inventory and multi-echelon transport with consolidation*

As presented above, multi-echelon systems are characterised by one or more groups of intermediary stages where various operations can be achieved. In these intermediary facilities, some operations take place, to help the distribution process, reduce costs, give a higher quality service or offer some additional services to vehicle drivers (Gonzalez-Feliu, 2008). One of the most important group of activities that take place at the intermediary platforms is related to consolidation and cross-docking operations (Brewer et al., 2001, p. 240). In most of multi-echelon transport cases, there is a cross-docking operation between two different vehicles (Jacobsen and Madsen, 1980; Min et al., 2002; Nagy and Sahli, 2007; Crainic et al., 2004). Another aspect associated to these facilities is that of storage and consolidation

(Brewer et al., 2001, p. 225). Freight can be deposed at the terminals for a small period of time (the necessary to complete the other operations); in these cases, the system can be modelled without considering inventory management approaches.

*Need and interests of multi-echelon transport approaches in cost optimisation*

If the two first meta-narratives deal with practical aspects of multi-echelon transport, the third is related to modelling and optimisation in transport research. From the consulted references, we observe than the main axes followed by scholars are the following. The first is that of mathematical modelling and analysis, related to the formalisation of models and formulations that can represent the optimisation problems, as well as the study of their limits. The second is that of exact methods that, starting from these models, propose algorithms based on applied mathematics concepts to find the real optimum. These methods are time consuming and are in general limited to situations with a small set of destinations. The third, which is the most developed, proposes heuristic methods that find a sub-optimal solution consuming fewer time in order to quickly find a good solution for small or big sets of destinations.

*Application issues of multi-echelon transport optimisation*

We can find several examples of multi-echelon distribution systems with cross-docking, as for example:

- The *postal and parcel delivery distribution systems* are in fact based on multi-echelon distribution, with several intermediary cross-docking platforms where freight is transhipped or consolidated. Such systems have been improved due to globalisation and the rise of international communications and trade (Gonzalez-Feliu, 2008).

- The *press distribution* sector usually has a transport network where the products are distributed to the stores through a system of consolidation platforms, in which they are re-packaged to be sent to the corresponding retailer (Jacobsen and Madsen, 1980; Gonzalez-Feliu and Morana, 2011).

- *Logistic systems for urban freight distribution* have also evolved into multi-echelon systems with consolidation platforms, called Urban Consolidation Centres (UCC). They are located in the periphery of the urban area and receive trucks to tranship goods into low-pollution vehicles that enter the city centres (Crainic et al., 2004).

- *Multimodal transport*, specifically the containerised distribution, is a classical example of a multi-echelon system with cross-docking where freight is conserved unaltered from its departure to the arrival at its final destination.

- *Grocery distribution* is a field which presents an heterogeneous group of supply chains. Some of them are based on distribution systems with cross-docking presenting several echelons.

- The *home delivery services and e-commerce* trends seem to be close to such systems to improve the service quality and decrease operational costs, more precisely with the development of intermediary reception points.

Many works in operations research deal with theoretical or computational issues and problems that are not always adaptable to practice. As we observed by analysing the selected references, many works in multi-echelon transport cost optimisation deal with real or realistic networks or transport plans. From the 95 selected sources, 11 of them are descriptive literature reviews, 4 of them are reference books on transport optimisation problems, 26 deal with theoretical or conceptual issues and 54 are computational papers. From them, 23 deal with location issues and will not be detailed in this work. The remaining 31 will be listed below, and we observed that half of them are related to real problems, such as milk collection in rural areas (4 papers), press distribution and postal services (4 papers), city logistics (3 papers), parcel delivery plans (2 papers), integrated supply chains with multi-echelon transport (1 paper) and road painting (1 paper). This seems not to be a lot but with respect to other similar combinatorial optimisation problems (such like the main variants of the vehicle routing problem or the travelling salesman problem), 50% is a high rate. Indeed, the number of applied papers in these fields are seldom higher than 25% although the developed algorithms are sometimes applied *a posteriori* to transport management systems and used in practice (Toth and Vigo, 2002, p. 5).

## 4. Two-echelon freight transport: concepts, definitions and notation

Consider a graph $G$ representing a multi-echelon transport system. Let us define the depot $V_0$ as the origin of the freight that has to be delivered. We assume that the depot facility has no limitations for the storage and the availability of the freight. The set of intermediate facilities will be called satellites and denoted by $V_S$. The set of customers will be denoted by $V_C$. Only one depot is defined, whereas the number of satellites and customers are respectively $N_S$ and $N_C$. The satellites are capacitated. The customers are the destinations of the freight and each customer $i$ has associated a demand $d_i$, i.e. the quantity of freight that has to be delivered to that customer. Two fleet of homogeneous vehicles are defined, one for each level. The number of vehicles is respectively $m_1$ and $m_2$. Each vehicle capacity is noted respectively $K^1$ and $K^2$. Each satellite $k$ is associated a capacity $m_{sk}$, defined by the maximum number of 2$^{nd}$-echelon vehicles that can be allocated to the satellite for cross-docking activities. The freight is considered to belong to the same type and the demand of each customer can not be split among different vehicles at the 2$^{nd}$-echelon. We consider that each satellite can be served by more than one 1st-level route and not all the satellites have to be visited.

Define the arc $(i,j)$ as the direct route connecting node $i$ to node $j$. If $(i,j)$ connects two satellites or the depot to one satellite we call it a 1$^{st}$-echelon arc, while if it connects either two customers or a satellite to a customer we have a 2$^{nd}$-echelon arc. A Hamiltonian circuit composed by only 1$^{st}$-echelon arcs is noted 1$^{st}$-echelon route. Analogously, a 2$^{nd}$-echelon route is supposed to contain only 2$^{nd}$-echelon arcs and starts and ends at the same satellite.

The problem is an extension to a two-echelon distribution system of the well-studied LRP (Nagy and Sahli, 2007), and is easily seen to be NP-Hard via a reduction to VRP, which is a special case of 2E-LRP arising when just one satellite is considered. According to the definition of 2E-LRP, if satellites' locations and assignments between customers and satellites are determined, the problem reduces to $1+n_s$ VRP (1 for the 1$^{st}$-echelon and $n_s$ for the 2$^{nd}$-echelon). The main question when modelling 2E-LRP is how to connect the two levels and manage the dependence of the second echelon from the first one.

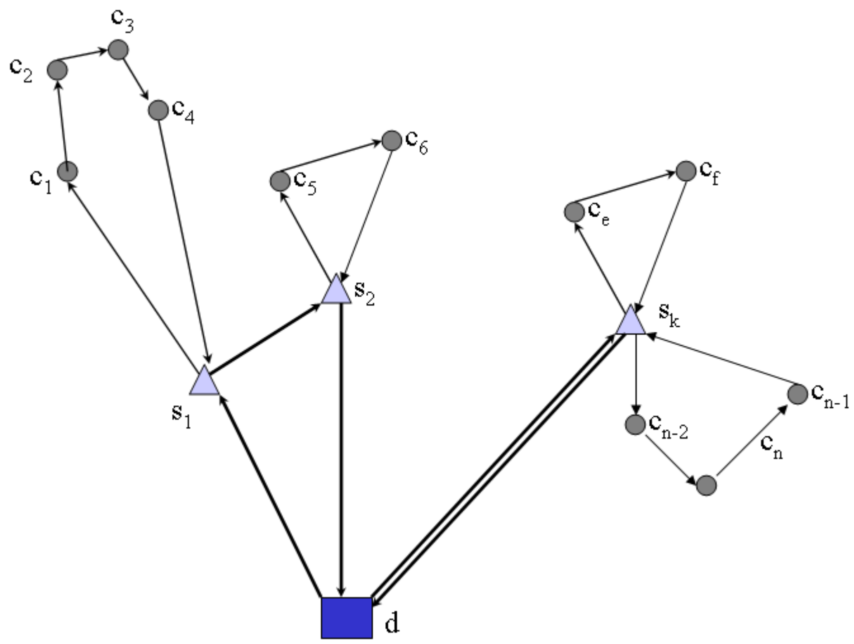


**Figure 2.** An example of a two-echelon transport system

## 5. Two-echelon LTL transport variants and solving methods

We can find in literature different families of problems, which are very similar. This problem is defined as the generalisation to N-echelon distribution systems of classical Location Routing Problem, i.e., the problem that seeks to simultaneously optimise the location of logistics platforms and the vehicle routes (Min et al., 2002). The two-echelon version of this problem was firstly introduced by Jacobsen and Madsen (1980) for a real decision problem with regard to a two-echelon distribution system. Laporte (1988) hypothesised the extension of this problem to multi-echelon transport. In the following we propose to synthesise three main approaches that take into account the multi-echelon nature of such systems. The first is that derived from vehicle routing and location-routing, which aims to optimise both the location of intermediary platforms and the vehicle routes in a systemic perspective. The second is similar but considers that the second echelon has a distributed demand on arcs and not on nodes. This is typical of postal services. The third approximates the second-echelon routes by fixing them (the number of possible routes is lower than that of the first approach) but takes into account the entire system for the solution computation.

### 5.1. "Freight allocation and vehicle routing" approaches

System route optimisation proposed to simultaneously optimise all the routes belonging to the various echelons, as well as the demand assignment to each intermediary platform. These approaches often follow the findings of Jacobsen and Madsen (1980), that defined the two-echelon version of the problem. This problem, that can be defined as two-echelon location routing problem (2E-LRP), consists of determining the location of the satellites, allocating the customers to the best satellites and determining both first-echelon and second-echelon routes.

**Table 2.** Main approaches and solving methods for category 1

| Authors | Type of algorithm | $N_D$ Max | $N_S$ Max | $N_C$ Max |
|---|---|---|---|---|
| Wren (1971) | 3-stage heuristic (clustering-allocation-routing using constructive heuristics) | 1 | Multiple (not specified) | 200 |
| Jacobsen and Madsen (1980) | Three route construction and satellite allocation procedures (two "initial solution" heuristics, one clustering first routing second with local search post-optimisation) | 1 | 3 | 4510 |
| Brunswicker (1986) | 3-stage heuristic (clustering-allocation-routing using constructive heuristics and local search post-optimisation) | 1 | 52 | 739 |
| Vahrenkamp (1989) | Savings algorithm, clustering first routing second algorithm for multi-depot problems | Multiple (not specified) | Multiple (not specified) | 200 |
| Semet and Taillard (1993) | Tabu search (two-step "initial solution" procedure improved by tabu search, where customers are reallocated if needed) | 1 | 9 | 45 |
| Semet (1995) | Clustering first routing second procedure (lagrangian relaxation) | 1 | 50 | 100 |
| Gerdessen (1996) | Combination of sequential heuristics, then improved by a selection of local search heuristics | 1 | 200 | 200 |
| Chao (2002) | Sequential procedure (cluster first route second "initial solution" and tabu search post-optimisation with customer reallocation moves | 1 | 150 | 199 |
| Drexl (2006) | Branch-and-Cut and Branch-and-Price | 1 | 8 | 8 |
| Scheuerer (2006) | Sequential procedure (clustering-based sequential insertion procedure with tabu search post-optimisation); procedures are then extended to multi-depot and multi-period variants | 1 | 150 | 199 |
| Tan et al. (2006) | Hybrid evolutionary procedure combining genetic operators, variable neighbourhood search and local search, in various combinations | 1 | 150 | 199 |
| Gonzalez-Feliu (2008) | Two mixed integer problem formulations, solved using XPRESS | 1 | 5 | 50 |
| Yang and Xiao (2008) | Hybrid heuristic method combining a two-step constructive algorithm and a branch-and-bound procedure | 1 | 1 | 1 |
| Lin et al. (2009) | Simulated annealing heuristic | 1 | 150 | 199 |
| Crainic et al. (2010) | Two-step fast heuristics (clustering first routing second with local search post-optimisation) | 1 | 5 | 250 |
| Nguyen et al. (2010) | Four constructive heuristic algorithms; GRASP algorithm with learning processes | 1 | 10 | 200 |
| Boccia et al. (2010) | Two-step constructive heuristic with Tabu Search post-optimisation | 5 | 20 | 200 |
| Gonzalez-Feliu et al. (2010) | Clustering-first routing-second algorithm with GRASP | 3 | 7 | 310 |

The N-echelon LRP has been hypothesised by Laporte (1998), Min et al. (2002), Nagi and Sahli (2007) and Gonzalez-Feliu (2008) without leading to a specific mathematical formulation for a generic N-echelon transport system. Most of the solving methods deal with two-echelon versions, which are the most easily transposable to real distribution issues, and heuristics are preferred to exact methods. This second type of problems has been proposed by few authors for small instances, in general less than 100 customers (Semet and Taillard, 1993; Drexl, 2006). The main limits of exact approaches is that they are slow and heavy in terms of calculation. For these reasons we will focus on heuristics. We report here a synthetic table of the proposed algorithms in literature:

### 5.2. "Freight allocation, 1st echelon vehicle and 2nd echelon arc routing" approaches

In these problems, the second echelon is not represented by a vehicle routing problem (where demand is assigned to nodes) but by an arc routing problem (where demand is distributed on an arc). These problems can deal with post distribution, waste collection or other road maintenance problems, like painting or repairing operations. Although in its one-echelon version (the Capacitated Arc Routing Problems) they are very popular, its two-echelon version (combining a vehicle routing problem to serve intermediary depots or facilities and an arc routing problem) is a new variant only studied by few authors. However, all of them deal with practical problems: waste collection in rural areas (De Pia and Filippi, 2006) and road painting (Amaya et al., 2007; 2010). All of them propose heuristics of different nature (one metaheuristic procedure, a combination of exact methods stopped before reaching optimum and one fast heuristic method), highlighting the importance of vehicle synchronisation.

**Table 3.** Main approaches and solving methods for category 2

| **Authors** | Type of algorithm | **$N_D$ Max** | **$N_S$ Max** | **$N_A$ Max** |
|---|---|---|---|---|
| Del Pia and Filippi (2006) | Variable Neighbourhood Descent with vehicle synchronisation | 1 | Multiple (not specified) | Real rural area (8500 inhabitants) |
| Amaya et al. (2007) | Cutting Plane and limited branch-and-bound procedure | 1 | 5 | 595 |
| Amaya et al. (2010) | Route first-cluster second heuristic method | 1 | 5 | 595 |

### 5.3. Network design approaches

In these problems, the main goal is not to precisely design each route plan but to give a general detailed definition of the two-echelon transport system. For this reason, costs are approximated, creating groups of customers that are then assigned to routes. We observe from Table 4 that this approximation allows to develop exact methods and use linear programs solved by commercial tools. The number of customers remain in many problems small.

**Table 4.** Main approaches and solving methods for the category 3

| **Authors** | **Type of algorithm** | **$N_D$ Max** | **$N_S$ Max** | **$N_C$ Max** |
|---|---|---|---|---|
| Crainic et al. (2004) | Mixed integer formulation solved using CPLEX | 1 | 12 | 51 |
| Ambrosino and Scutellà (2005) | Mixed integer formulation solved using CPLEX | 1 | 5 | 25 |
| Gendron and Semet (2008) | Mixed integer formulation solved using CPLEX | 93 | 320 | 722 |
| Brotcorne et al. (2010) | Mixed integer formulation solved using CPLEX | 1 | 5 | 5 |
| Huart et al. (2010) | Sequential procedure (constructive "initial solution" heuristic and tabu search post-optimisation ) | 1 | 5 | 50 |

## 6. Conclusions and research guidelines

In this paper a study of two-echelon transport based on a systematic review is proposed. A meta-narrative method was applied to operations research works in order to find the main stakes related to multi-echelon transport optimisation. Moreover, a systematic review on the proposed solving methods, as well as other modelling approaches, allowed us to unify concepts and propose a first mixed integer model that resumes the main optimisation problem. The main works deal with realistic cases of two-echelon systems, in order to answer to real tactical and operational planning questions. We also observe that the system structure in multi-echelon distribution planning is becoming important in cost optimisation approaches. However, few reference instances are used, thus the comparison among various methods is difficult. A standard notation and one or more sets of instances will facilitate the development of methods for these problems.

In this field, several research directions can be observed. The first direction is more conceptual and refers to modelling the different optimisation problems and solving approaches, focusing on advanced urban freight distribution systems and supply chain management decision support planning. The second direction is related to the difficulties related to connecting two echelons, a subject few studied but very challenging from a theoretical and conceptual point of view. These studies will allow the researchers to find the most interesting methods to find more efficient solving procedures. The third direction is the development of exact methods, which are currently limited to some specific problems or to very small instances. These methods are good for real applications like those of cases presented as category 3. Finally, the question of the real application of these methods to practice still remains. This was not the aim of this paper, but it will be important to discuss about it, mainly on the bases of a qualitative analysis and quantitative statistics on the uses of these methods on real transport cases. The fourth direction, which is the most advanced at the moment, is that of heuristics. However, the latest meta-heuristic advances in VRP have not been applied to more complex systems, and they would constitute an interesting research direction to meet the exigencies of real applications. Moreover, multidisciplinary analysis are required in order to meet the practice needs and develop solving methods that are both robust and accurate in the context of transport planning for real cases, that can be seen as a fifth direction. In any case, this problem seems to be a prominent optimisation problem directly related to real transport planning questions.

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