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COST OPTIMISATION IN FREIGHT DISTRIBUTION WITH CROSS-DOCKING: N-ECHELON LOCATION ROUTING PROBLEM

ABSTRACT

Freight transportation constitutes one of the main activities that influence the economy and society, as it assures a vital link between suppliers and customers and represents a major source of employment. Multi-echelon distribution is one of the most common strategies adopted by the transportation companies in an aim of cost reduction. Although vehicle routing problems are very common in operational research, they are essentially related to single-echelon cases. This paper presents the main concepts of multi-echelon distribution with cross-docks and a unified notation for the N-echelon location routing problem. A literature review is also presented, in order to list the main problems and methods that can be helpful for scientists and transportation practitioners.

KEY WORDS

location-routing problems, multi-echelon distribution, cross-docking, combinatorial optimisation, literature review

1. INTRODUCTION

The freight transportation sector is continuously changing as a consequence of the growth and transformation of the economic activity. In recent years the companies have changed their inventory and distribution strategies for their better adaptation to the changing demand. In these strategies, the cost and performance management are crucial to the survival of firms in a long-term perspective [1]. This work deals with multi-echelon distribution with cross-docking, which consist of transportation networks where intermediary consolidation platforms are used. In these systems, no inventory policies are involved, i.e. the transported goods can be temporarily stored at intermediary platforms but they do not have warehousing functions. The main examples of such systems are the following:

- *Postal and parcel delivery distribution systems* use intermediary cross-docking platforms where freight is transhipped or consolidated [2]. Such systems have been improved due to globalisation.
- In the *press distribution* network 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 retailers [3].
- *Logistic systems for urban freight distribution* have also evolved into multi-echelon systems with consolidation platforms, called Urban Consolidation Centres (UCC), mainly located in the periphery of urban areas [4].
- *Multimodal transportation*, specifically the containerised distribution [5], is a multi-echelon system with cross-docking where freight is conserved unaltered from its departure to the arrival at its final destination.
- *Grocery distribution*, in particular the schemas related to *just-in-time supermarket supply chains* [6] and *e-grocery services* [7] seems to be close to such systems.
- *Transportation sharing approaches*, i.e. collaborative transportation agreements where several operators share their capacities and resources [8], need multi-echelon cross-docking systems to better optimise the resources involved in the shared schemas.

Although multi-echelon transportation systems are very common in both real practice and research fields, it is difficult to identify the significant works related to multi-echelon transport cost optimisation because of the different notations used and the lack of unification in the works proposed. Indeed, many problems have been developed for specific applications and they do not always follow the traditional notation of vehicle routing problems. The aim of this paper is to formalise the travel cost optimisation problems of multi-echelon distribution systems with cross-docking platforms in a conceptual way. To do this, we make a brief overview on combinatorial optimisation methods as well as a generic formulation that englobes and unifies the notation of the main variants found in the scientific literature. In Section 2, the main notions of vehicle routing optimisation are briefly presented. Then, in order to illustrate and classify the main variants found in literature, we propose in Section 3 a general formulation and the unification of the main notation terms. After that, a synthetic review of the scientific works related to multi-echelon LRP is proposed. As conclusion, the main guidelines on further researches based on the literature review will also be enounced.

2. A NOTE ON VRP AND LRP VARIANTS

The Vehicle Routing Problem (VRP) is the generic name given to a whole class of combinatorial optimisation problems in which a set of destinations, called customers, have to be visited by a fleet of vehicles based at one or several depots. In particular, the objective is to minimise the total cost of a set of routes, each performed by a single vehicle that starts and ends at its own depot. These routes will fulfil each customer's requirement and satisfy all the operational constraints. Many works and surveys related to VRP can be found in literature [9, 10].

The basic version is that of capacitated VRP (CVRP) where vehicles have a maximum capacity, the same for each vehicle. In the function of the context and the important parameters that define the transportation system, several variants have been developed. The most popular ones are VRPs with time windows, multi-depot VRP and VRP with heterogeneous vehicle fleets [9].

Another important group of problems is defined when customers do not only receive freight, but some quantity of goods must be also collected there. We will not focus on these problems, called pickup and delivery problems (PDP) since they are beyond our study context. However, they are interesting and a recent review can be found in literature [11].

The Location Routing Problem (LRP) is related to a network composed of two types of nodes, i.e. facilities and customers, and one or more fleets of vehicles, each of them defined by its capacity. In this network, costs are associated both to vehicle routes (travel costs) and to facilities (allocation, activation and facility usage costs). The LRP seeks to minimise the total cost by simultaneously selecting a subset of candidate facilities and constructing a set of delivery routes that satisfy a number of constraints. In these problems, the facility location and the routing problems are not solved separately but are considered as a more complex problem [12]. Nagy and Sahli [13] propose complete reviews of this problem, focusing on single stage, multiple facility LRP. Moreover, the authors also present some multiple-stage LRP cases, highlighting the difficulty of identifying them.

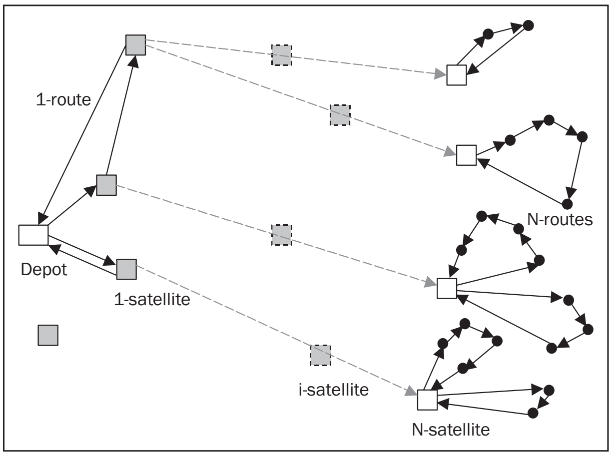

Figure 1 - Example of an N-echelon distribution network

3. THE NE-LRP: CONCEPTS AND GENERAL FORMULATION

Consider an *N*-echelon distribution system composed of *N* stages. To represent it in graph *G* three types of nodes are defined. The *depots* are defined as the starting points of the distribution. An intermediary facility associated to the stage *e* is defined as *e-satellite*. At an *e*-satellite, the freight is transhipped and no inventory and warehousing activities are allowed. The *customers* are defined as the final destinations of the freight. The customers are also noted as *N*-nodes on graph *G*. The overall transportation network can then be decomposed into *N* echelons:

- the 1^{st} echelon, which connects the depots to the 1^{st}-echelon intermediary facilities;
- $N-2$ intermediate echelons interconnecting the different intermediary facilities;
- the N^{th} echelon, where the freight is delivered from the $(N-1)^{th}$ echelon intermediary facilities to the final destinations.

To deliver the freight, a number of vehicle fleets are defined. Each echelon e usually has its own fleet of vehicles. An *e*-echelon vehicle is a vehicle belonging to echelon *e*, i.e. travelling from an *e*-1-satellite to an *e*-satellite.

The depots will be represented by a set noted V_0, the customers by the set V_c and each set of *e*-satellites will be denoted by V_s^e. Each *e*-satellite can be capacitated, and this capacity can be noted as the maximum number ms_k^e of $e+1^{st}$ echelon vehicles that *e*-satellite s_k^e can host. Moreover, each customer *i* has an associated demand d_i to be delivered. Each e^{th} echelon vehicle can serve more than one *e*-satellite in the same route, and each *e*-satellite can be served by any number of e^{th} echelon vehicles, or by none. Each e^{th} echelon vehicle has the same capacity K^e. Each *e*-satellite has a fleet of m_h^e vehicles. We define y_k^{ie} as e^{th} echelon route, which is a Hamiltonian circuit made by an e^{th} echelon vehicle; this circuit starts from *e*-1-satellite *k*, serves one or more *e*-satellites and ends at the departure node *k*.

The main question when modelling NE-LRP is how to connect the different echelons and to manage the dependence of each e^{th} echelon from its predecessor. We present a Mixed Integer Programming Model for a generic NE-LRP. The presented formulation is based on set-partitioning problems [9], used for the classical LRP and VRP variants, and applied to multi-echelon systems. In order to formulate the MIP model, three types of variables are used.

The first type of variables are the route variables y_k^{ie}, a {0, 1} variable that shows if the Hamiltonian circuit *i* starting at *e*-1-satellite *k* is used or not. Each variable y_k^{ie} represents a feasible route, defined by its cost, its serviced nodes and the order in which they are visited. It has, among other things, to respect capacity and length constraints. We introduce attribute δ_{hk}^{ie} to indicate if *e*-node *k* is served by *e*-route *i* starting at *e*-1-node *h*. The second type of variables is related to the freight passing through the cross-docking facilities. We define a real variable D_k^e that indicates the freight quantity cross-docked at *e*-satellite *k*, as well as D_{hk}^e for the freight quantity going from (*e*-1)-satellite *h* to *e*-satellite *k*. Moreover, we define a {0, 1} variable noted I_k^e that indicates if *e*-satellite *k* is used ($I_k^e = 1$) or not ($I_k^e = 0$). Each variable y_k^{ie} belongs to the set of possible e^{th}-echelon routes R_e.

We suppose that the freight having to be delivered to each customer *c* is not split into different vehicles. Moreover, each *e*-satellite receives freight from at most one (*e*-1)-satellite but can be delivered by more than one e^{th}-echelon vehicles. Three types of costs are considered. The cost of each route y_k^{ie} is noted c_k^{ie}. The set-up cost of satellite s_k^e and the unitary cost of transhipment and other operations at this satellite are noted SL_k^e and S_k^e, respectively.

The model is defined as follows:

$$\min \sum_{e=1}^{N} \sum_{k \in V_s^e} \sum_{i \in R_e} c_k^{ie} y_k^{ie} + \sum_{e=1}^{N} \sum_{k \in V_s^e} S_k^e D_k^e + \sum_{e=0}^{N} \sum_{k \in V_s^e} SL_k^e I_k^e \quad (1)$$

s.t.

$$\sum_{k \in V_s^{N-1}} \sum_{c \in V_c} \delta_{ck}^{iN} y_k^{iN} = 1 \quad \forall i \in R_N \quad (2)$$

$$m_h^e I_h^e \geq \sum_{k \in V_s^{e-1}} \sum_{i \in R_e} \delta_{hk}^{ie} y_k^{ie} \quad \forall e \in \{1,\dots,N\}; \forall h \in V_s^e \quad (3)$$

$$\sum_{k \in V_0} D_k^0 = \sum_{c \in V_c} d_c \quad \forall k \in V_s^e \quad (4)$$

$$\sum_{h \in V_s^e} D_h^e = \sum_{k \in V_s^{e+1}} D_k^{e-1} \quad \forall e \in \{1,\dots,N\} \quad (5)$$

$$D_h^e = \sum_{k \in V_s^{e-1}} D_{hk}^e \quad \forall e \in \{1,\dots,N\}, \forall h \in V_s^e \quad (6)$$

$$D_k^e = \sum_{h \in V_s^{e+1}} D_{hk}^{e+1} \quad \forall e \in \{1,\dots,N\}, \forall k \in V_s^e \quad (7)$$

$$D_k^{N-1} = \sum_{i \in VR_N} \delta_{ck}^{iN} d_k \quad \forall e \in \{1,\dots,N\}, \forall k \in V_s^e \quad (8)$$

$$D_{hk}^e \leq \sum_{i \in R_e} \delta_{hk}^{ie} y_k^{ie} K^e \quad \forall e \in \{1,\dots,N\}, \forall h \in V_s^e \quad (9)$$

$$\begin{aligned} &y_k^{ie} \in \{0,1\} && \forall i \in R_{e-1}, \forall k \in V_s^{e-1}, \forall e = \{1,\dots,N\} \\ &D_k^e \in \Re^+ && \forall k \in V_s^{e-1}, \forall e = \{1,\dots,N\} \\ &I_k^e \in \{0,1\} && \forall k \in V_s^{e-1}, \forall e = \{1,\dots,N\} \end{aligned} \quad (10)$$

The objective function to minimise (1) is the total cost resulting from the addition of transportation costs and the satellite's activation and operations costs. Constraints (2) show that each customer is served by only one route. In case of customers having demand that exceeds the capacities of N-vehicles, they will be represented as a number of customers receiving full vehicles, plus another one transporting the remaining load. Constraints (3) show the limits of capacity for each satellite, and constraint (4) and (5) assure the demand conservation, i.e. the overall load transported by all the vehicles of each echelon is the same as the overall customers' demand. Finally, constraints (6), (7), (8) and (9) assure the link between (*e*-1)-routes and *e*-routes. The nature of the decision variables is formulated in (10).

The problem is easily seen to be NP-Hard via a reduction to VRP, which is a special case of NE-LRP arising when just one echelon and one satellite (with no travel cost from the depot to the satellite) is considered. According to the definition of NE-LRP, if the assignments between customers and satellites are determined, the problem is reduced to

$$1 + \sum_{e=1}^{e=M} n_{se}$$

VRP (1 for the first echelon and n_{se} for each e^{th} echelon, where n_{se} is the number of *e*-satellites having freight allocated).

This formulation involves a huge number of variables that have to be generated. Column Generation could then be implemented to N-echelon systems in order to produce lower bounds and solve the problem using Branch-and-Price [14]. However, solving the NE-LRP in an exact way is difficult, and the calculation times increase exponentially with the addition of each connection constraint, i.e., the addition of an e-satellite in the graph. In order to show the main solving methods and to make a state-of-the-art of NE-LRP solving nowadays, we propose a literature review in the next section.

4. NE-LRP VARIANTS AND SOLVING METHODS : REVIEW OF THE SCIENTIFIC LITERATURE

In this section, we present the main works related to multi-echelon location routing, in a chronological way. Wren first studied this problem [15] for a real milk collection problem, and Jacobsen and Madsen [3] formalised the problem as a 2E-LRP. The authors propose three fast heuristics in order to apply them to a real decision problem for a real press distribution case involving intermediary facilities and cross-docking. The first one assimilates the 2^E-LRP to a Steiner Tree Problem, and solves them with a heuristic combining a greedy algorithm and a 3-opt procedure. The second one is composed by the Alternate Location Allocation [16] and the Savings algorithm [17]. The third one combines a Savings algorithm and the DROP method of Feldman et al. [18]

Wren [15], Brunswicker [19] and Vahrenkamp [20] propose several heuristics in order to solve a variant of this problem where the 1st echelon routes can visit some customers. In their approach, each 211th echelon route visits only a satellite. This problem presents the particularity that each 1st echelon vehicle is a truck-and-trailer convoy that represents then two 2nd echelon routes. In all three cases, a clustering-allocation-routing heuristic procedure is presented. These algorithms are constructive heuristics. Semet and Taillard [21] propose an algorithm that finds an initial solution using a sequential algorithm and improved by Tabu Search [22, 23], where customers can be reallocated. Semet [24] proposes a clustering first routing second solution method where customers are first allocated to 1st echelon routes then the resulting routing problems are solved via Lagrangian relaxation. Gerdessen [25] assumes that all customers have unit demand and each 1st echelon route visits only one satellite. Initial solutions are found using a number of sequential heuristics. These are then improved by a combination of VRP local search procedures.

Chao [26] develops a two-phase algorithm where in the first phase an initial solution is obtained with a cluster first route second heuristic and the second phase improves the initial solution using Tabu Search with customer reallocation moves. Scheuerer [27] proposes a clustering-based insertion procedure using a Sweep algorithm [28] improved by Tabu Search. Moreover, the author adapts the proposed heuristic to a multi-depot and the multi-period 2E-LRP.

Drexl [29] proposes a general formulation for a 2E-LRP with taxi services, i.e. a generalisation of the problem proposed by Wren [15] to 2 echelon and many satellites visited by each 1st level vehicle. The problem is solved using branch-and-cut and branch-and-price. Tan et al. [30] present a hybrid evolutionary algorithm that uses specialised genetic operators, a variable-length representation and a local search method. The authors propose also a genetic algorithm and compare the two methods. Gonzalez-Feliu et al. [31] propose a MIP formulation for a simplified 2E-LRP with no location costs derived from multi-commodity network design to study the limits and the general behaviour of the mathematical model. The model is tested on four sets of instances using Xpress linear programming solver. The authors also introduce some cuts which make the calculation time decrease. Moreover, four sets of instances available at OR Library website [32] are proposed. Optimal solutions are found for instances up to 21 customers and lower bounds are presented for all the instances.

Hoff and Løkketangen [33] propose a Tabu Search algorithm for solving a multi-depot, multi-period 2E-LRP with heterogeneous vehicles for a real-world case, improving on the existing tour plans used by their industry partner. Tuljak-Suban and Twrdy [5] define the two-echelon VRPPD, which is an extension of this problem. The problem is modelled in the context of empty container repositioning in a feeder system. After a detailed analysis of the northern Adriatic ports and the feeder connections with the hub ports of the Mediterranean, a model is proposed for decision support to port authorities.

Lin et al. [34] propose a simulated annealing algorithm, then computational tests on the instances proposed by Chao [27] are presented to compare the proposed SA algorithm to previous works. Crainic et al. [35] develop a route optimisation methodology for a generalised two-echelon freight distribution system. Two models are proposed: a service network design model for the 1st-echeon vehicles, which approximates the second echelon routing costs giving a first estimation of the overall costs; then a second model optimises the 2nd-echelon trip costs considering the first-echelon vehicle movements. Crainic et al. [36] make a satellite location analysis showing the impact of the number and the location of used satellites. The authors build and solve instances with up to 250 customers thanks to a two-phase heuristic based on a clustering first routing second algorithm plus a classical local search procedure.

Boccia et al. [37] consider the design problem of two-echelon freight distribution systems by defining the structure of a 2E-LRP for a real application. The problem is then solved by a meta-heuristic combining a constructive procedure improved by Tabu Search post-optimisation that connects the two echelons by proposing moves that modify routes of both echelons at the same time. This method can solve real large size instances. Nguyen et al. [38] propose four constructive heuristics and one meta-heuristic to solve the LRP-2E with capacity constraints on vehicles and satellites. The best heuristic builds giant tours over the set of customers, each tour being limited by the capacity of a first-level vehicle. The giant tours are then partitioned using a splitting procedure that inserts the satellite depots. A TSP is finally solved to visit the satellites selected. The proposed meta-heuristic is a greedy randomised adaptive search procedure (GRASP) reinforced by a learning process. The same authors [39] also present a hybrid metaheuristic combining a GRASP procedure and an evolutionary/iterated local search (ELS/ILS) to solve a

2E-LRP. The GRASP procedures uses three constructive heuristics followed by local search to generate an initial solution, then an intensification strategy is carried out by a dynamic alternation between ELS and ILS, using Tabu Search.

Only one problem involving more than two echelons is found in literature. Ambrosino and Scutellà [40] propose a mathematical programming formulation for several NE-LRP up to five echelons. In order to explore the computational complexity of the models, a linear program is proposed to find the optimal solution or at least provide lower bounds for problem instances based on a real-life case. The optimal solution could only be found for the smallest problem instance, a 3E-LRP involving two depots, five 1-satellites, five 2-satellites and twenty-five customer zones. As the problem instances become larger, the gap between the best integer solution found, within a time limit of several days for the large instances.

5. CONCLUSIONS AND RESEARCH GUIDELINES

In this paper a general conceptualisation and notation for NE-LRP is proposed. A detailed review on the main variants of the problem, the proposed solving methods, as well as other modelling approaches, are presented. The main works deal with realistic cases of two-echelon systems, and the vehicle routing and location-routing approaches are dominant. Moreover, the system structure in multi-echelon distribution planning is becoming important in cost optimisation approaches. The reviewed models and solving methods are mainly built to answer real tactical and operational planning questions, more precisely in two-echelon food and urban distribution applications.

Until now, few reference instances have been used, thus the comparison among various methods is difficult. A standard notation and one or more sets of instances (the most used are those proposed by Chao [27], Gonzalez-Feliu [31] et al. and Nguyen et al. [38]) will facilitate the development of methods for these problems. Moreover, three research directions can be observed. The first, more conceptual one, is related to modelling different NE-LRP variants and similar approaches for realistic situations, focusing on advanced urban freight distribution systems and supply chain management decision support planning. The first 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 lower bounds, in order to develop more efficient solving procedures. The second direction is the development of exact methods, which are currently limited to some specific problems or to very few instances. Branch-and-bound and branch-and-cut are preferred to other methods, but also branch-and-prize has to be considered as a solving method for these problems. The third 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 such as NE-LRP, and they would constitute an interesting research direction to meet the exigencies of real applications. In any case, the NE-LRP seems to be a prominent optimisation problem directly related to real transportation planning questions.

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RÉSUMÉ

OPTIMISATION DES COÛTS POUR LES SYSTÈMES DE DISTRIBUTION MULTI-ÉCHELON AVEC CROSS-DOCKING : LE PROBLÈME DE LOCALISATION-OPTIMISATION DES TOURNÉES À N ÉCHELONS

Le transport de marchandises est l'une des principales activités qui affectent l'économie et la société, car elles assurent un lien vital entre les fournisseurs et les clients et représentent une source importante d'emplois. La distribution à échelons multiples est l'une des stratégies les plus communes adoptées par les transporteurs dans un objectif de réduction des coûts. Bien que les problèmes de tournées de véhicules sont très communs dans la recherche opérationnelle, ils sont essentiellement liés à des cas à un seul échelon. Cet article présente les principaux concepts de la distribution à échelons multiples, et introduit une notation unifiée pour le problème de la localisation et d'optimisation des tournées de véhicules dans des systèmes à N échelons. Une revue de la littérature est également présentée afin d'énumérer les principaux problèmes et les méthodes qui peuvent être utiles pour les scientifiques et les professionnels du transport.

MOTS-CLÉS

problèmes de localisation et tournées de véhicules, distribution à échelons multiples, transbordement de marchandises, optimisation combinatoire, revue de la littérature

RESUMEN

OPTIMIZACIÓN DE COSTES EN SISTEMAS DE DISTRIBUCIÓN MULTINIVELES CON CROSS-DOCKING: EL PROBLEMA DE LOCALIZACIÓN-RUTADO A N NIVELES

El transporte de mercancías constituye una de las principales actividades que influyen en la economía y la sociedad, ya que asegura un vínculo vital entre proveedores y clientes

y representa una fuente importante de empleo. La distribución multinivel es una de las estrategias más comunes adoptadas por las empresas de transporte en un objetivo de reducción de costes. Aunque los problemas de rutado de vehículos son muy comunes en investigación operativa, están esencialmente relacionados con los casos de un solo nivel. Este trabajo presenta los principales conceptos de la distribución multinivel con trasbordo de la mercancía, así como una notación unificada para el problema de localización y rutado a N niveles. Una revisión de la literatura también es presentada, a fin de enumerar los principales problemas y métodos que pueden ser útiles para los científicos y los profesionales del transporte.

PALABRAS CLAVE

problemas de localización y rutado, distribución multinivel, trasbordo de mercancías, optimización combinatoria, revisión de literatura.

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