The multi-attribute two-echelon location-routing problem with fleet synchronization at intermediate facilities

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1. Introduction

Freight distribution systems play an important role to support the economic and social development of cities. At the same time, urban freight transportation also hiders urban life in terms of congestion, noise, and pollution. To this matter, *city logistics* concepts have been proposed seeking to promote efficient and sustainable freight transportation of the rising urban demands while reducing negative externalities. Multi-echelon, especially two-echelon logistics systems, has become a mean to help mitigate these problems and improve urban freight distribution in terms of economic, social, and environmental viability (Crainic, Ricciardi, and Storchi 2009).

Planning the infrastructure locations and the appropriate vehicle routes to dispatch customer demands on-time is crucial in the city logistics context. The *two-echelon location routing problem (2ELRP)* is one of the frameworks of choice to model this integration of facility location and vehicle routing decisions on two-echelon layouts. In recent years, however, the interest of academics and practitioners has been shifting toward more realistic multi-attribute two-echelon problem settings. Mostly driven by the major opportunity that these attributes represents for the logistics industry in the upcoming years (Crainic and Montreuil 2016). Nevertheless, the literature in more realistic 2ELRPs characterized by several interacting attributes is still very limited (Dellaert et al. 2018). Particular developments are required in the 2ELRP literature, especially in relation to time-dependent components of the operation, non-substitutable demands, the synchronization of the

carriers involved and the modeling and the algorithmic challenges these considerations imply. This work aims to provide a methodological framework to respond to these challenges and contribute toward the filling of the gaps in the present literature.

We study the *multi-attribute two-echelon location-routing problem with fleet synchronization at intermediate facilities (MA-2ELRPFS)*. Prompted in particular by *City Logistics* applications, the problem settings we address include time-dependent multi-commodity (non-substitutable) demand, time windows, limited storage capacity (if at all) at intermediate facilities, and synchronization at these intermediary facilities of the fleets operating on different echelons. The system, illustrated in Figure (1), is composed of sets of suppliers (demand origins), platforms, satellites (the intermediate facilities), and customers (demand destinations), as well as two garages, one for the capacitated vehicles operating at each echelon. Demand is defined between suppliers and customers, each individual demand being characterized by origin, destination, volume, availability time window at origin, and due time window at destination. The system requires the selection of facilities at both levels, the allocation of each OD demand to an existing platform and the routing and scheduling of vehicles on each echelon to deliver the freight from platforms to customers, through satellite facilities. In this context, satellite facilities are considered shared infrastructures without storage capacity. Hence, to allow efficient transshipment operations, vehicles from each echelon must be synchronized in time at the same facility. A careless handling of the synchronization may result in freight being held at an intermediate facility for long time which may, in turn, result in additional handling/storage costs or in certain cases in an infeasible operation. Therefore, determining vehicle and demand departures and delays at satellites and platforms facilities are required to meet economic and service quality targets.

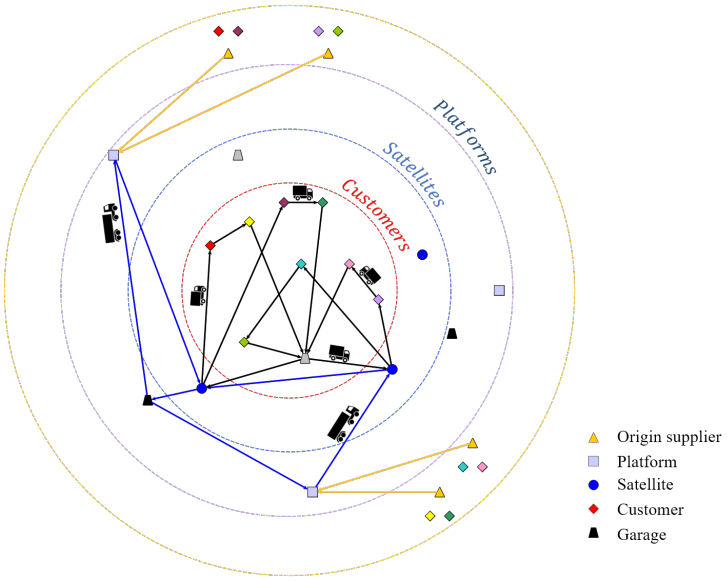


Figure 1 **Example of a feasible solution for a MA-2ELRPFS.**

We present and compare two mixed-integer programming formulations, notably an arc-based and a time-expanded formulation for the MA-2ELRPFS. Similarly, an exact solution framework for the MA-2ELRPFS based on a dynamic discretization scheme is proposed to address the scalability issues provoked by the time-expanded formulation. In the computational study, we analyze the cost sensitivity, the infrastructure usage and the importance of fleet synchronization under time sensible distribution systems to derive managerial insights.

2. Solution framework for the time-expanded model

The MA2ELRP deals with the several interacting attributes, in which time represents a fundamental factor. To achieve on-time shipments in a cost-effective manner, it is crucial to define at what time vehicles should wait or depart from the right facility. From a modeling perspective, it is challenging to represent these decisions due to the level of details required. Time-space or time-expanded network representations are broadly used to model the time dependency of demands and vehicle operations, as well as of synchronization requirements. Typically, a time-expanded network discretizes the planning horizon considered into a finite number of time periods, and duplicates the nodes of the original network in all relevant periods; Arcs then stand for inter-period movement and in-facility work/wait activities. Time-expanded networks rise issues concerning how time periods are defined. Short periods provide detail but make problem solving very difficult, while longer time periods may yield insufficient solution quality. Compounding the difficulty of our problem, demand generates compulsory time moments that must be explicitly included in the time-space network representation.

We therefore define a dynamic discretization framework for the time-expanded model to address this scalability drawback, building on the method introduced by Boland et al. (2017) for the service network design problem. In general, our solution framework employs partially time-expanded networks, resulting from reducing the complete time-expanded representation of the problem with a specialized prepossessing scheme and a coarser granularity for the time interval. The solution framework iteratively refines this reduced time-expanded network and solves the integer program defined by its network configuration to extract lower and upper bounds for the MA-2ELRPFS to solve the problem to optimality, or within a specified tolerance. The solution framework dynamically determines a sufficiently refined reduced network that provides a feasible solution space for the MA-2ELRPFS without creating a complete time-expanded network. The particular characteristics of the MA-2ELRPFS, of the routing decisions, in particular, boost the iterative growth of the reduced time expanded network. We, therefore, developed specific refinements to keep the time-expanded network as small as possible while accounting for the time-dependent properties of the problem.

3. Experimental study

Computational experiments are extensively performed to study the efficiency of the proposed formulations and the solution framework for the MA-2ELRPFS. All experiments were conducted on a single machine with Intel(R) Core(TM) i7-7800X with 128 GB of RAM running Linux. Both mathematical formulation and the proposed solution framework were implemented in C++ using IBM ILOG CPLEX concert technology 12.9. Since the MA-2ELRPFS is a new problem, no instances are available in the literature. We modify well-known datasets for the 2EVRPTW (Dellaert et al. 2018) to generate MA-2ELRPFS instances. We investigate the performance of the two formulations in terms of LP relaxation as well as runtime and solution quality. Finally, when testing the solution framework, we analyze the cost sensitivity, the infrastructure usage and the importance of fleet synchronization under time sensible distribution systems to derive managerial insights.

4. Conclusions

The results of the numerical experiments show the efficiency of the proposed solution method, as well as the benefits to the city logistic network of integrating multiples attributes into a single formulation. The computational study demonstrates that the time-expanded formulation formulation provide a stronger LP relaxation against the arc-based formulation. Similarly, the iterative refinement procedure performs well on a comprehensive set of instances and provides optimal guarantees that otherwise cannot be handled by two proposed models by a general-purpose MIP alone.

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