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A Simulation-Optimization Approach for the Two-Echelon Location Routing Problem Arising in the Creation of Urban Consolidation Centres

Eine simulationsgestützte Optimierung des mehrstufigen Location Routing Problems im Kontext urbaner Konsolidierungszentren

Aljoscha Gruler, Angel A. Juan, Universitat Oberta de Catalunya,
Barcelona (Spain), agruler@uoc.edu, ajuanp@uoc.edu

Astrid Klüter, Markus Rabe, TU Dortmund, Dortmund (Germany),
astrid.klueter@tu-dortmund.de, markus.rabe@tu-dortmund.de

Abstract: With rising urban population numbers around the world, innovative city logistics concepts such as the creation of urban consolidation centres are gaining increased attention from practitioners and researchers. A common optimization challenge arising in this context is the two-echelon location routing problem (LRP-2E), which combines facility location and vehicle routing decisions in multi-level supply chains. However, most existing solving methodologies for this problem setting are purely optimization-focused and make simplifying assumptions about the availability and accuracy of input variables. This work discusses the integration of simulation techniques into a heuristic multi-start optimization framework to solve the LRP-2E with stochastic customer demands. Computational experiments are conducted with real-life data based on a fast-moving consumer goods supply chain in the metropolitan area of Athens.

1 Introduction

The establishment of efficient and sustainable city logistics systems is of major importance in the creation of liveable, environmentally-friendly, and healthy urban areas (Taniguchi et al. 2014). In this context, collaborative supply chain strategies constitute promising approaches to reduce the negative effects of road freight transportation (Leitner et al. 2011; Pomponi et al. 2015). On the one hand, operational cooperation includes the exchange of customer orders, vehicle capacities, and information between different supply chain actors. On the other hand, tactical and strategic collaboration concepts involve higher degrees of collaboration. Moreover, collaboration concepts are typically long-term focused agreements in contrast to more short-term focused operational cooperation scenarios. One promising collaboration concept to reduce the negative externalities of urban road freight transportation involving an advanced level of company interaction is the construction of urban consolidation centres (UCCs). Instead of directly serving customers located within city borders from different delivery points, consolidated final customer deliveries from one or several companies are completed from these satellite facilities, which are typically situated near to city. This allows for using smaller delivery trucks with higher vehicle utilization levels (Savelsbergh and van Woensel 2016).

Through the construction of UCCs, multi-level distribution networks are supported from which a range of combinatorial optimization problems (COPs) can be deducted. While satellite locations are typically defined through the capacitated location routing problem (CLRP) (Prodhon and Prins 2014; Quintero-Araujo et al. 2016), multi-level vehicle routing problems (VRPs) such as the two-echelon VRP arise in the creation of efficient delivery routes (Cattaruzza et al. 2015). The two-echelon LRP (LRP-2E) solved in this work combines these NP-hard optimization problems. An illustrative LRP-2E example solution can be seen in Figure 1. Apart from establishing first-level (from the central depots to the UCCs) and second-level (from the UCCs to the final customers) routing plans, the most efficient satellite facilities from a set of possible locations need to be defined.

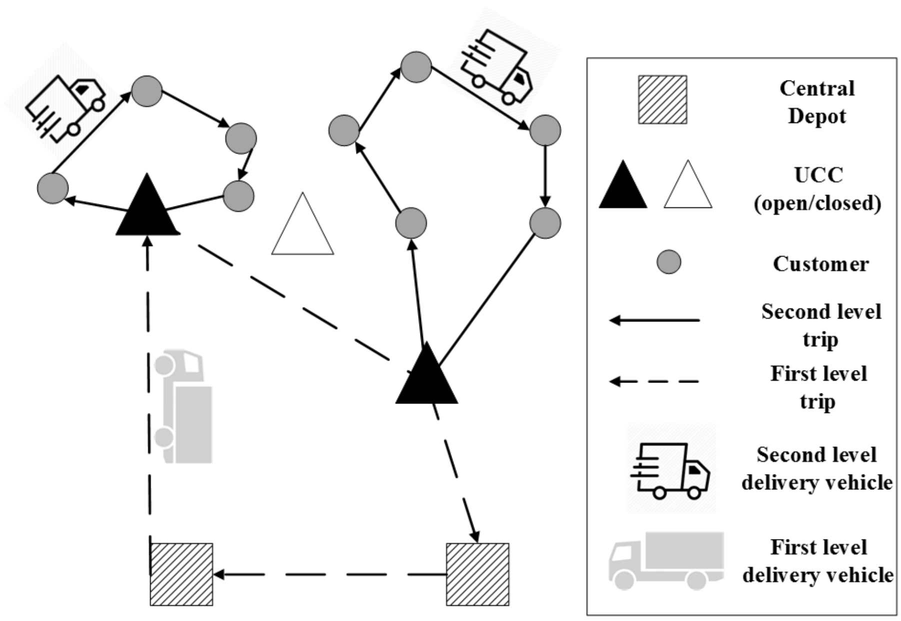

Figure 1: *Example of a LRP-2E solution*

Most solving methodologies for the LRP are only able to solve oversimplified versions of the problem by assuming all necessary information (e.g. travel times, customer demands, etc.) to be perfectly known in advance. To overcome this drawback, we introduce Monte Carlo simulation into a heuristic solving framework based on biased randomization (Juan et al. 2013). By simulating different uncertainty scenarios concerning final customer demands, our simheuristic approach

(Juan et al. 2015) allows for considering stochastic objective function estimates in the solution construction. Moreover, the simulation phase yields further decision-making information, which can be used to establish a risk/reliability analysis of different LRP-2E solutions.

In this paper, relevant literature is reviewed in Section 2; our simheuristic solving methodology is outlined in Section 3; Section 4 describes the experiment design based on a real-life case study with several hundred customer nodes and various potential capacitated UCC locations to test the performance and behaviour of our solving framework; finally, Section 5 concludes this work and highlights possible future research lines.

2 Related Work

A comprehensive survey on two-echelon routing problems was recently presented by Cuda et al. (2015). The authors highlighted three problem extensions according to the involved level of tactical and strategical planning decisions:

1. the tactically focused two-echelon VRP in which routing plans between different echelons are established;
2. the two-echelon LRP in which strategic facility location decisions are included; and
3. truck-and-trailer problems, in which customers are served by different trucks and trailers according to a set of restrictions.

The authors conclude that the current literature on two-echelon routing problems is still lacking the consideration of input uncertainty.

Drexl and Schneider (2015) have reviewed relevant literature on variants and extensions of the location-routing problem. Even though multi-echelon problem settings were not considered, the authors highlighted the use of simulation to solve the LRP with stochastic demands as done by Mehrjerdi and Nadizadeh (2013). These authors proposed a greedy clustering method to solve the capacitated location routing problem. In this method, customer demands are simulated using fuzzy logic. The same authors later extended their solving approach with an Ant Colony Optimization metaheuristic (Mehrjerdi and Nadizadeh 2016). While their solving methodology has similarities to the one described in this paper, the authors do not consider multiple echelons. Furthermore, our simheuristic allows for applying any kind of probability distribution, instead of relying on fuzzy logic to account for demand stochasticity.

Recently, further extensions to the LRP-2E have been presented. Rahmani et al. (2015) introduced the two-echelon, multi-product LRP with Pickup and Delivery (LRP-MPPD-2E). They put forward two types of local search methods for the routing and location part of the algorithm. Later, Rahmani (2016) proposed a mixed-integer linear model for small-scale instances and extensions of some nearest neighbour and insertion approaches for the same problem setting. The author developed new clustering-based approaches for location routing problems. Computational experiments showed that the clustering approach is very competitive and outperforms other heuristics for smaller problem instances with less than 200 nodes. Dalfard et al. (2013) applied hybrid genetic and simulated annealing algorithms for the LRP-2E with vehicle fleet capacity and maximum route length constraints. The authors compared their results to solutions obtained with the software LINGO, suggesting that their proposed algorithm is more effective. Vidović et al. (2016) presented a mathematical formulation of a two-echelon location-routing problem in case of recycling logistics networks. Collecting points between end customers and transfer stations are defined using a mixed-integer linear programming model that maximizes the profit and creates a distance-dependent collection rate. For solving large problem instances, the authors put forward heuristic solving approaches.

3 Solving Approach

A flowchart of our simheuristic solving framework for the LRP-2E with stochastic demands can be seen in Figure 2. During a predefined stopping criterion (a maximum number of iterations is used in this work), *m* satellite facilities are randomly opened while ensuring that the overall UCC capacity can serve overall final customer demands. Within each algorithm iteration, the first-level routing costs between the central depots and the opened UCC locations are calculated with a nearest neighbour heuristic. It is assumed that a single vehicle tour is sufficient to stock all these UCCs. Moreover, different routing maps are established by assigning a sub-set of all final customers to each UCC by a round-robin criterion. Hereby, each UCC iteratively 'chooses' the next customer to be served from the non-assigned clients according to its geographical proximity.

Subsequently, different delivery routing plans are established for each routing map consisting of a satellite location and the assigned sub-set of final customers. Within a multi-start framework, an efficient routing plan is created by using a biased-randomized version of the well-known Clarke-and-Wright savings (CWS) heuristic (Clarke and Wright 1964). Whereas the original savings heuristic constitutes a greedy solution construction procedure, biased randomization is used to introduce a probabilistic behaviour during the establishment of new routing plans (Juan et al. 2013). Based on a geometric distribution parameter α ($0 < \alpha < 1$), edges are added to the currently constructed solution according to their expected savings values. Hereby, edges with higher savings values are more likely to be added to a solution with probabilities biased towards the most promising edges.

During this optimization phase, deterministic (expected) final customer demands $E[D_i]$ are considered at each client *i*. Whenever the deterministic costs of a new single VRP solution *newSol* outperform the deterministic costs of the currently incumbent solution *currentBest*, it undergoes a simulation phase to account for demand uncertainty. The simulation procedure is only applied to promising deterministic routing plans to avoid jeopardizing computational times through extensive simulation runs. For each promising *newSol*, final customer demands of each client are simulated from a lognormal probability distribution during *nSim* simulation runs. We assume that our simheuristic methodology is flexible enough to incorporate any other kind of suitable probability function at this stage. In order to construct the lognormal distribution, expected demand values $E[D_i]$ are used as distribution mean. Furthermore, stochastic demands are formulated as $Var[D_i] = k \cdot E[D_i]$, which allows for considering different demand variance levels *k*. The special case of a variance level equal to zero ($k = 0$) corresponds to the deterministic problem setting.

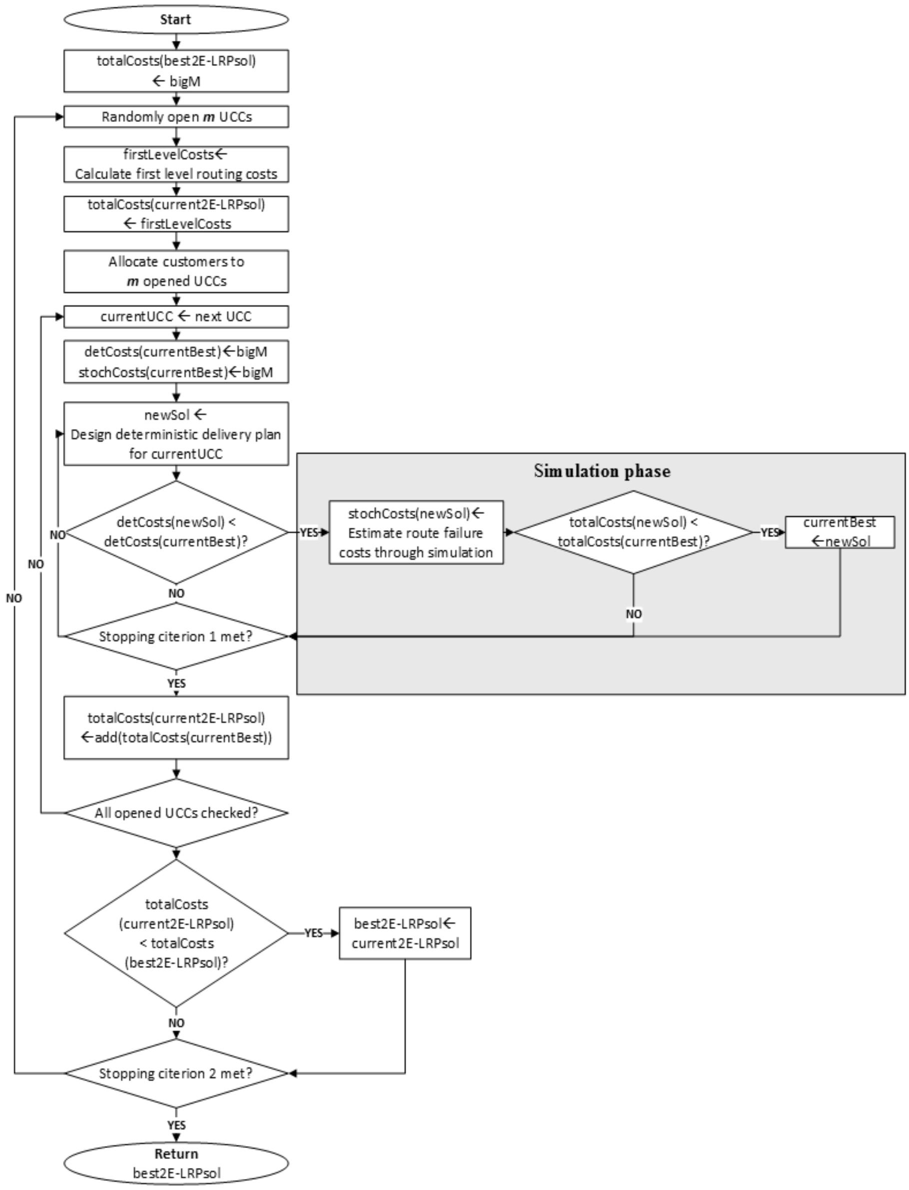

Figure 2: *Flowchart of Simheuristic solving methodology for the LRP-2E*

Due to the stochastic nature of customer demands, a vehicle completing a pre-established delivery route might run out of stock before the planned route is completed whenever simulated demands exceed the vehicle capacity. In cases of such route failures, an additional trip to the corresponding UCC is necessary. For this reason, a route failure is penalized with a round trip from the customer at which the vehicle runs out of stock to the respective satellite location. The total route failure costs occurring during the simulation phase are considered in order to estimate the expected stochastic costs of an established solution. Thus, the total costs of a new single VRP solution are estimated as the sum of the deterministic routing costs and the expected route failure costs obtained during the simulation phase. Whenever the total costs of any *newSol* outperform the total costs of the current best found solution *currentBest*, the incumbent solution is updated.

Once the multi-start algorithm for a single UCC and its assigned clients is completed, the described process is repeated for all opened satellite locations. Finally, the quality of a LRP-2E is defined as the total routing costs (considering the deterministic and stochastic values) of serving all clients in addition to the first-level routing costs to stock all UCC locations. The inclusion of simulation in the described procedure leads to two kinds of advantages: On the one hand, a reliable estimate of the overall solution costs in an uncertainty scenario is obtained. On the other hand, the expected route failure costs calculated during the simulation are used to define incumbent VRP solutions for each UCC to guide the heuristic solution search under the consideration of stochastic customer demands. Moreover, the simulation phase allows for comparing different LRP-2E solutions along additional decision dimensions, instead of solely focusing on expected routing costs. Indeed, decision-takers might be interested in information such as the standard deviation or different quantiles of results obtained during the simulation runs, as a possible measure of the reliability associated with a solution.

4 Experimental Design and Analysis of Results

The simheuristic algorithm is implemented as a Java application and run on a personal computer with 4GB RAM and an Intel Pentium processor with 2.16GHz. The necessary algorithm parameters to complete the tests described in the following are defined as follows:

- Geometric distribution parameter α: 0.3 (defines the selection probabilities of different edges during the biased randomized solution construction procedure)
- Multi-start stopping criterion 1: 10 iterations (defines the number of created LRP-2E solutions)
- Multi-start stopping criterion 2: 200 iterations (defines the number of times the CWS heuristic is applied to construct new single-VRP solutions)
- Simulation runs *nSim*: 500
- Demand variance *k*: 2
- UCC capacity: 1000
- First-level vehicle capacity: 5000
- Second-level vehicle capacity: 100

To validate our simheuristic solving framework, it is tested on a real-life case based on a fast-moving consumer goods supply chain operating in the metropolitan area of Athens (Greece). A total of 342 customers scattered around the city centre are currently directly supplied from five different depots (highlighted with the warehouse symbols in Figure 3). All depots, UCCs, and customer locations are given as geographic longitude and latitude coordinates. Distances between any two nodes are calculated as Euclidean distances. The overall costs (calculated with the biased randomized CWS in combination with simulation as described) of serving all customers with the current depot and customer assignments and no satellites are outlined in Table 1. All clients are currently served on 22 routes with a deterministic routing distance of 1895 km. Additionally, route failure costs mount to an expected value of 179 km.

Table 1: *Current costs of serving all customers without the use of UCCs*

Depot	# UCCs	# Customers	Demand	Det. Costs	Stoch. Costs	Total Costs	# Routes
1	0	63	372	375	32	407	4
2	0	87	479	586	75	663	5
3	0	105	607	413	36.	449	7
4	0	42	213	215	11	226	3
5	0	45	230	304	24	328	3
Total	0	342	1901	1895	179	2074	22

In order to test the effect of collaboration among suppliers in a city logistics context, five random UCC locations around the city centre are defined. Figure 3 outlines the geographic locations of all these satellite locations (star symbols). As a larger vehicle is used to complete the first level-routes, the routing costs for the replenishment to all UCCs are multiplied by 2, as proposed by Nguyen et al. (2012).

Figure 3: *Location of depot and UCCs*

The ten best 2E-LRP solutions are listed in Table 2. The best solution yields total costs of 1284.62, outperforming the current non-collaborative solution by over 38%. Moreover, the results suggest that a lower number of UCCs leads to the best overall LRP-2E results. However, the stochastic costs seem to decrease with a higher number of opened UCCs, since a higher number of satellite locations decreases the penalization costs of returning to the UCC in case of route failures.

Table 2: *Overview of different LRP-2E solutions*

Sol	# UCCs	Det. Costs	Stoch. Costs	First-level Costs	Total Costs	# Routes
1	2	975	76	232	1284	20
2	2	1047	96	222	1366	21
3	2	1033	93	240	1367	20
4	2	1093	81	232	1407	20
5	3	1158	80	240	1478	20
6	4	1302	81	247	1632	21
7	4	1332	49	254	1637	22
8	4	1341	55	241	1638	22
9	4	1438	68	241	1748	22
10	5	1556	68	251	1875	22

5 Conclusions

This work proposes a simheuristic solving methodology for the two-echelon location routing problem (LRP-2E) arising in the establishment of urban consolidation centres (UCCs) in city logistics. By integrating simulation into a heuristic multi-start procedure based on biased randomization, stochastic final customer demands are taken into account. The algorithm has been tested on a real-life supply chain setting in the Greek capital Athens with various depots and over 300 final customers. A comparison between the current non-collaborative case and the establishment of satellite locations (UCCs) to consolidate last-mile deliveries suggest potential savings of nearly 40%.

Various potential problem extensions can be defined to extend this work. The experimental setting could be made more realistic by considering UCC opening costs, which are not accounted for in this work. Likewise, the effect of vehicle safety capacities could be investigated. From the aspect of customer modelling, a more extensive analysis of different demand variance levels and simulation results regarding standard deviations or different quartiles for a closer risk analysis could be completed. Furthermore, our solving methodology could be extended to include further input uncertainty associated with travel times or customers. Even dynamic inputs could be considered by combining our algorithm with machine-learning techniques.

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