The collaborative vehicle routing problem with consistency and workload balance

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1. Motivation

The transportation industry has become a very competitive environment. While the number of competitors has grown considerably, customers have become more and more demanding. Therefore, companies need to provide efficient transportation services at low prices to be competitive on the market. For this reason, profit margins have sensibly declined. To increase their efficiency, carriers can establish collaborations in which they share their fleets with the aim to maximize their profit and reduce operational costs. Collaborations may be centralized, where decisions are made by an external decision maker having complete information. In decentralized collaborations, no such fully informed decision maker exists. Obviously, centralized collaborations allow a better exploitation of the available resources. Collaborations or shared resources do not only increase efficiency of logistics providers, but are also demanded by other stakeholders. Residents, for example, benefit from efficient transportation, since emissions of harmful substances and road congestions are reduced. However, while residents and public authorities aim for ecological goals, the objective for each individual carrier is to maximize her own profit. For this reason, carriers are interested in entering collaborations only if they have a benefit.

Several studies on collaborations in vehicle routing problems have been presented in the literature (Gansterer and Hartl 2018), but none of them addresses periodic or multi-period problems. Collaborations where carriers own customers being serviced on a regular basis, face the problem of (i) time consistency in terms of visiting time, and of (ii) service consistency (Groer, Golden,

and Wasil 2009). The latter ensures that customers are visited by the same collaboration partner throughout the whole planning horizon. This is a practically relevant assumption, since it is knwon that service consistency increases customers satisfaction and improves loyalty and operations efficiency (Kovacs et al. 2015). Furthermore, collaborative transportation systems are often feared to suffer from *winner-takes-all effects*, which lead to solutions where a small share of carriers serve the great majority of customers. To avoid this unbalanced workloads, a minimum number of customer served by each carrier should be defined.

The goal of this work is to analyze the impact of consistency and workload balance in centralized collaborative transportation systems. The objective is to (i) maximize total collaboration profit, to (ii) ensure an increment of profit for all participants, and to (iii) provide high-level customer service, ensuring both time and service consistency. For this purpose, we introduce and formulate the multi-period vehicle routing problem with time and service consistency and workload balance (Co-ConVRP-WB). We strengthen our formulation by several valid inequalities. For solving large instances, we design an efficient and effective matheuristic (MH) and an iterated local search (ILS) algorithm. Our computational study provides meaningful managerial insights.

2. Problem Description

In this work we introduce the Co-ConVRP-WB, in which a set of carriers, K, has to serve a set of customers I with identical goods, over a planning horizon consisting of P periods. Each carrier k owns a subset of the total customers, A_k, but carriers can collaborate and share customers among each others if it is beneficial for both the grand coalition and for each single carrier. Every customer i requires to be visited in a given subset of the periods in P or eventually in all of them. For each visit to a customer j, the required service time s_j^p and the quantity to be delivered, q_j^p, are known. To collect the revenue of a customer, π_i, it is necessary to perform all required visits. Carriers may freely exchange customers among each other, but, for consistency purposes, all the tasks related to the same customer must be performed by the same carrier. Each carrier owns a fleet located on a given depot D_k, composed by V_k identical vehicles of capacity Q_{max}. Each vehicle can perform a single route per period. The duration cannot exceed a maximum duration, T_{max}, and the cumulative load cannot exceed Q_{max}. The set of nodes involved in the network, N, is composed by $\cup_{k \in K} D_k \cup I$. Travel cost and time between each pair of nodes, i and j, are known as c_{ij} and t_{ij}, respectively. To avoid the *winner-takes-all effect*, the number of customers assigned to a carrier k cannot be lower than the number of customers owned by k ($|A_k|$), decremented by a maximum allowed quantity α_k. For time consistency purposes, the difference between the arrival time at customer i in two service periods, must differ with at least δ time units. The goal of the problem is to maximize the total profit of the carriers, which is calculated by the difference between

Table 1 Aggregated results for small instances: collaboration profits (MH and ILS) vs. best known solutions. The last column shows the increase in collaboration profit, if workload and consistency constraints are omitted.

Instance	MH	ILS	No constraints
pr01	0.09%	0.02%	1.54%
pr02	0.07%	0.04%	0.95%
pr03	0.00%	0.00%	0.90%
pr04	0.09%	0.01%	1.13%
⋮	⋮	⋮	⋮
Avg.	0.05%	0.01%	1.13%

the total revenue and the total travel costs. In addition, the profit of each carrier must not be lower than the profit obtainable by the same carrier if it does not enter the collaboration (R_k).

3. Solution Approach

We present a MIP formulation and several valid inequalities to strengthen it. Using this model, we are able to solve only small-sized instances, therefore, to handle larger instances, we propose a matheuristic and an ILS algorithm. For the MH, we start from an initial feasible solution obtained by running the MIP with a short time limit (10 seconds). Then we apply a first improvement local search in which we explore a neighborhood obtained by fixing the customer assignment and the routing planning for $|K| - 2$ carriers and, by this, solve only a small subproblem. However, both customer assignment and routing are optimized. Every time an improving solution is found, it is kept as current best solution, and the local search procedure is restarted. The method stops when all pairs of carriers have been tested without obtaining any further improvement. The ILS procedure uses MH as local search operator. Whenever a local minimum is reached, a perturbation is applied to the current best solution, such that that n randomly chosen customers must be assigned to a different carrier than in the current solution. Finally, we restart MH with the solution obtained by the perturbation. The ILS is supposed to avoid that the procedure gets trapped in local minima.

4. Results and Discussion

Computational tests have been carried out on (i) small-sized instances with 20 customers (with a total of 49 visits), 4 periods and 4 carriers, and on (ii) large-sized instances with 50 customers (with a total of 150 visits), 6 periods and 8 carriers. The MIP runs with a time limit of 3600 seconds. However, it is able to handle only the small-sized instances, within an average computational time of 1198 seconds. Furthermore, only 6 out of 10 instances can be solved to optimality, while for the other 4, the model reaches the time limit with a very small optimality gap of 0.41% on average. Aggregated results for small instances are presented in Table 1.

We observe that MH is obtaining near optimal solutions, with an average gap of only 0.05% compared to the best solution found with the MIP, within a very short average computational

time of 26 seconds. Since ILS contains a random component, it has been run 10 times for each instance to analyze its robustness. Computational results show that, on average, ILS is able to obtain solutions with only 0.01% gap to the best MIP solution within an average runtime of 96 seconds. During the 10 repetitions of each instance, it reaches the best known solution at least once. The improvement on the total profit for the grand coalition is 9.15% on average. Interestingly, the solution quality does not increase if time consistency or workload balance constraints are omitted. Service consistency decreased the total collaboration profit by only 1.13% on average. Thus, our study reveals that these requirements do not come with additional cost, which might be a strong argument for carriers to enter collaborations. On the large-sized instances the MIP is not able to find even a feasible solution within the given time limit. Therefore, we compare solutions obtained by MH against ILS and against the initial solution without collaboration. MH is able to improve the global profit of 9.6%, on average with an average computational time of 337 seconds, while ILS performs slightly better with an average improvement of 10.97% in 478.7 seconds on average.

5. Conclusion

We introduced a new multi-period VRP, where collaboration among carriers, service and time consistency as well as workload balance are simultaneously taken into account. To address this problem, we formulated a mathematical model, and proposed several valid inequalities. By this, we were able to solve small-sized instances. In order to tackle larger instances, we designed an efficient and effective MH, and an ILS based on it. A numerical study revealed that both methods reach near optimal solutions within very short computational times. We could show that the total collaboration gain is about 10%. This is less than typical collaboration gains reported in the literature (e.g. Gansterer and Hartl 2018). However, the gap stems from the fact that we ensured that each carrier has to yield a minimum individual collaboration profit.

Dropping the workload balance and time consistency constraints, we did not observe an increase in collaboration profit. Service consistency decreased the total collaboration profit by only 1.13% on average. This revealed that both balancing and consistency requirements can be imposed with almost no additional cost, which is a meaningful managerial insight and a strong argument for carriers to enter collaborations.

References

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