A SAVINGS ANALYSIS OF HORIZONTAL COLLABORATION AMONG VMI SUPPLIERS

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Abstract. This paper considers a logistics distribution network with multiple suppliers that each replenish a set of retailers having constant demand rates. The underlying optimization problem is the Cyclic Inventory Routing Problem (CIRP), for which a heuristic solution method is developed. Further, horizontal collaboration through a third party Logistics Service Provider (LSP) is considered and the collaborative savings potential is analyzed. A design of experiments is performed to evaluate the impact of some relevant cost and network structure factors on the collaborative savings potential. The results from the design of experiments show that for some factor combinations there is in fact no significant savings potential.

1. Introduction. Increasingly tougher market conditions such as increasing competition, higher customer requirements and rising fuel costs force companies to look for new ways to coordinate their logistics operations more efficiently. Traditional research in operations management focuses mainly on tools to optimize internal operations such as production planning, capacity investments and allocations, inventory decisions and shipment schedules. However, companies and academics have become aware that the operational performance also depends on the decisions of other players in the supply chain. Therefore, a shift from single-firm optimization to ‘supply chain management’ occurred and collaboration among various supply chain players became the next target in order to achieve higher operational efficiency ([15] and [18]).

Supply chain collaboration is defined as ‘two or more independent companies that work jointly to plan and execute supply chain operations with greater success than when acting in isolation’ ([21]). By establishing collaboration in a supply chain, the focus of companies shifts from a local perspective to a more global perspective and companies try to optimize the global supply chain performance rather than their own performance. Supply chain collaboration can be vertical, i.e., among companies on subsequent levels of the supply chain, and horizontal, i.e., among companies on the same supply chain level.
In the distribution logistics literature, three types of contributions can be found in the papers on horizontal collaboration: (i) case study reports, e.g., from the forestry industry ([12]) and the furniture industry ([2] and [3]); (ii) qualitative frameworks for successful implementation, identifying the benefits and impediments ([22], [9], [1] and [4]), and (iii) quantifying the collaborative benefits and how to share these in a fair way among the participants. This is mostly performed using operations research techniques to model the costs and/or profits of the partners and to share the potential savings of collaborating among the partners ([5], [11], [17], [12], [13] and [23]).

Vertical collaboration in distribution logistics is achieved by implementing Vendor Managed Inventory (VMI). Under VMI, the ‘vendor’ (a distributor or supplier) takes over the responsibility for making decisions regarding the timing and quantity of the replenishments to its ‘customers’ (usually retail stores). The retailers share their inventory data with the supplier, who can then design more cost efficient routes by coordinating the replenishment decisions. As such, VMI decreases the total inventory and transportation cost for the supplier and his customers. The planning problem in VMI of jointly managing inventory at the retailers and designing vehicle routes for replenishment is known as the Inventory-Routing Problem (IRP). Moin and Salhi ([16]), Andersson et al. ([1]) and Coelho et al. ([8]) present comprehensive overviews and classifications of the literature on the IRP.

There is also some research on combined horizontal and vertical collaboration, known as ‘lateral’ collaboration. Most of this research also focuses on its theoretical aspects, such as necessary frameworks and requirements to successfully implement lateral collaboration. E.g., Mason et al. ([14]) stress the importance of lateral collaboration to reach optimized transportation solutions. However, to the best of our knowledge, no previous research has been done in which a quantitative model is developed to quantify and evaluate the impact of combined horizontal and vertical collaboration in distribution logistics.

This paper considers a combination of vertical and horizontal collaboration in distribution logistics. We consider a distribution system in which multiple suppliers (or ‘vendors’) vertically collaborate with their retailers in a VMI framework. Further, these suppliers can choose to outsource their distribution logistics activities to a third party Logistics Service Provider (LSP), which thus enables horizontal collaboration among the suppliers. The contribution of this work to the academic literature lies in the adaptation of the heuristic solution method for the resulting IRPs with multiple suppliers that can collaborate through the LSP and the deployment of this solution method to quantify the benefits from the collaboration of the suppliers using controlled computational experiments. A design of experiments is performed to evaluate the impact of problem characteristics on the savings potential of a collaborative alliance between suppliers and the LSP.

The remainder of this paper is organized as follows. Section 2 provides a detailed problem description and introduces the formal notation. Section 3 elaborates the heuristic solution method for the underlying inventory routing problem and the savings calculation model. An illustrative example is given in Section 4. Section 5 deals with the computational experiments and statistical analyses to identify the important characteristics of the costs and network structure for the savings creating potential. Finally, Section 6 presents the final conclusions and further research avenues.
2. Formal problem description. In this paper, we aim to manage the logistics activities in a supply chain, more specifically the distribution and inventory management, in a more holistic way by introducing combined vertical and horizontal collaboration. We consider a two-echelon distribution network consisting of a set of suppliers $S$ (indexed by $s$) that each have to replenish their own set of retailers $J_s$ under a VMI policy. An LSP that offers logistic services to the suppliers is introduced. The LSP can look for multiple suppliers to take over their distribution and hence enable horizontal collaboration among them. When replenishing their retailers, all suppliers have two options: they can work individually, which means they replenish their retailers from their own warehouse using their own vehicles, or they can outsource these activities to the LSP, who then stores the goods at its central warehouse and replenishes the retailers from there. If multiple suppliers outsource to the LSP together, they form a coalition $C$ (a subset of $S$), and their retailer sets are joined into retailer set $J_C = \bigcup_{s \in C} J_s$. The LSP can then combine deliveries to the retailers of these different suppliers, which could lead to more cost efficient routes. We compare the stand-alone costs of individually operating suppliers with the supply chain costs of supplier coalitions under the LSP. Furthermore, we identify how characteristics of the retailers, suppliers and LSP impact the collaborative savings potential.

Because of the intermediary role of the LSP, several hurdles are avoided to successfully implementing horizontal logistics collaboration ([9]), such as the suppliers’ reluctance to share sensitive information with competitors or the difficulties suppliers encounter to find suitable partners. Since the LSP is no direct competitor, it is easier to establish trust between the suppliers via this third party.

Given that supply chain collaboration requires long-term commitment of the involved parties, we adopt a long-term perspective. Because of the vertical collaboration, the suppliers or LSP get to decide when they replenish the retailers and with what quantity, as long as no stock-outs occur. Furthermore, we assume that the retailers (indexed by $j$) all have a fixed daily demand rate $d_j$ (in units per day), such that a cyclic solution approach is appropriate. Therefore, the integrated inventory management and replenishment planning problem at hand is the Cyclic Inventory-Routing Problem (CIRP) ([19] and [20]).

We design a model that minimizes the total of the distribution costs of the suppliers (or LSP) and the inventory holding costs of the retailers. The model has to be able to solve a CIRP for each individual supplier $s$ from $S$, but also for coalitions $C$ of the suppliers $S$. To be able to solve these large-scale CIRPs within reasonable computational time, we adopt a heuristic solution approach.

When considering an individual supplier, we assume he operates from his own warehouse, which is then the start and end point of all routes. When considering the LSP, the start and end point of the routes change to the central warehouse of the LSP.

When the suppliers outsource their distribution logistics, they have to remunerate the LSP for his services. This remuneration is left undetermined in our model, since it is only a money transfer between the suppliers and the LSP, but does not represent an actual cost the suppliers incur.

When solving a CIRP, a set of routes $R$ needs to be constructed such that each route $r \in R$ visits a subset $J_r$ of the retailer set $J_s$ (in case of an individual supplier) or $J_C$ (in case of a coalition $C$ of suppliers under the LSP). The costs that are taken into consideration are:
1. A vehicle loading and dispatching cost $\varphi_0$ per iteration of route $r$
2. A travel cost per iteration of route $r$, which is the travel distance $D_r$ of the route, multiplied by the travel cost per km $\tau$.
3. A service cost $\varphi_j$ per delivery at retailer $j$ for unloading the goods
4. An inventory holding cost $\eta_j$ per unit per day at retailer $j$

Apart from the aforementioned assumption that all retailers have a constant demand rate, the following assumptions are made:

- Stock-outs at the retailers are not allowed and their inventory levels cannot exceed their maximum capacity $\kappa_j$.
- The replenishments of the retailers are strictly periodic (i.e., the number of days between two consecutive deliveries is constant).
- A retailer is always replenished by the same vehicle in the same route.
- The suppliers or LSP always have sufficient inventory available in their warehouse to load vehicles that are being dispatched.
- A vehicle’s driving time is limited to 8h per day.
- A homogenous fleet of vehicles with a capacity of $\kappa$ units is available.

Within our CIRP model, all routes are repeated periodically. The time between two consecutive iterations of a route $r$ is its cycle time $T_r$. The vehicle load, given by $T_r \cdot \sum_{j \in J_r} d_j$, is limited to the vehicle capacity $\kappa$, and the delivery quantity to an individual retailer, $T_r \cdot d_j$, is limited by the retailer storage capacity $\kappa_j$. As a result, the cycle time is restricted to a maximum cycle time $T_{\text{max},r}$.

$$T_{\text{max},r} = \min \left( \left\lfloor \frac{\kappa}{\sum_{j \in J_r} d_j} \right\rfloor, \min_{j \in J_r} \left\lfloor \frac{\kappa_j}{d_j} \right\rfloor \right)$$

The total cost rate of route $r$ is denoted $TC_r$. It varies with the route’s cycle time $T_r$ since the distribution costs ($\tau D_r, \varphi_0$ and $\sum_{j \in J_r} \varphi_j$) are incurred once every $T_r$. Conversely, the delivery quantities and thus the inventory holding costs of the retailers in the route increase with $T_r$: $\sum_{j \in J_r} \frac{1}{2} \eta_j d_j T_r$. The optimal cycle time $T_{\text{eoq},r}$ balances the distribution costs and the retailer inventory holding costs in an EOQ-like manner, while taking into account $T_{\text{max},r}$ (see [19, 20]).

$$TC_r = \frac{1}{T_r} \left( \tau D_r + \varphi_0 + \sum_{j \in J_r} \varphi_j \right) + T_r \sum_{j \in J_r} \frac{\eta_j d_j}{2}$$

$$T_{\text{eoq},r} = \min \left( \sqrt{\frac{2 \left( \tau D_r + \varphi_0 + \sum_{j \in J_r} \varphi_j \right)}{\sum_{j \in J_r} \eta_j d_j}}, T_{\text{max},r} \right)$$

For a given set of retailers, solving the CIRP thus corresponds to partitioning the retailers into subsets and designing a route for each subset, such that the total cost rate of all routes is minimized.

3. Solution method. To solve the large-scale CIRPs, we adopted the state-of-the-art metaheuristic solution algorithm developed by Raa and Dullaert ([20]). This algorithm uses a two-phase heuristic embedded in a metaheuristic framework for the design of the routes.
Two-phase route design heuristic. The route design heuristic constructs an initial solution using a merge-based heuristic in a first phase, and then improves that solution using local search operators in the second phase.

The construction heuristic is an adaptation of the well-known Clarke-and-Wright heuristic ([7]) to the situation of the cyclic IRP. It starts with a separate route per retailer and then starts evaluating whether merging routes can result in a cost rate reduction. The evaluation of a merge of two routes involves checking the feasibility and determining the reduction in travel distance, but it also requires the merged route's maximal and optimal cycle time to be calculated in order to minimize the merged route's cost rate. The merge-based heuristic iteratively evaluates all possible route merges and implements the merge that leads to the largest cost rate reduction, until no merges are left that can reduce the cost rate.

The second phase of the route design is an improvement phase with various local search operators. These local search operators evaluate whether making a small, local adjustment to a given solution (a local search ‘move’) could improve its cost rate, by checking the feasibility of the adjustment, recalculating maximal and optimal cycle times, and determining the resulting effect on the cost rate.

The following local search operators (all with quadratic complexity) are being used.

1. 2-opt: remove two arcs (either from the same route or from two different routes) and replace them by two other arcs, such that all routes are closed again and no subtours are created.
2. Relocate: remove a retailer and try inserting it into another position (either in the same route, in a different route or in a separate new route).
3. Exchange: switch the positions of two retailers (either from the same route or from two different routes).

The local search operators are implemented using a modified best-accept strategy. In a single iteration of the local search operator, a list is created of all feasible and improving moves and then sorted according to improvement value. After this, all retailers are marked as unaffected and the execution of moves from the list starts. When a move is encountered that does not involve affected retailers, that move is executed and the retailers involved in the move are marked as affected (to avoid performing two moves with the same retailers in a single iteration). Thus, during a single iteration of an operator, not just the best move is executed, but multiple moves can be executed. This drastically improves computational efficiency.

Further, when applying a local search operator, it is reiterated until no more improvements are found before moving on to the next local search operator. Thus, we only consider a single operator at a time and cycle among the operators until neither finds an improvement anymore. This further improves computational efficiency without significantly affecting overall solution quality.

Metaheuristic framework. The two-phase route design heuristic builds a single solution for the cyclic IRP. With a small adjustment, this heuristic can be reused as the building block in a metaheuristic framework that generates multiple solutions (and retains the best found).

The adjustment is made in the construction heuristic of the route design. Instead of always implementing the best possible merge, this is randomized somewhat, such that the order in which routes are being merged is changed and hence different solutions are created in different runs of the construction heuristic.
The adjusted construction heuristic is then used in a population-based metaheuristic framework. In that metaheuristic, a new solution (or ‘offspring’) is created from two ‘parent’ solutions in a ruin-and-recreate manner. Two parents are selected from the population and common arcs in these solutions are identified. Then, a random number of retailers is removed from one of the parent solutions, but only retailers that are not incident to common arcs can be removed. After that, the resulting partial solution that remains after removing some of the retailers, is reoptimized. This is done by reinserting the retailers that had been removed, each in a separate route, and then applying the two-phase route design heuristic outlined above.

Since all of the solutions in the population are being optimized using the local search operators, the intensification of the search process is already very strong. Therefore, the population management in the metaheuristic framework is used for diversification. This is done by explicitly measuring the diversity among the individuals in the population, based on the number of common arcs and the number of unique arcs across solutions in the population. A solution that has more common arcs with other solutions in the population will have a lower diversity score. Selecting a solution as a parent for creating offspring is then done based on the diversity scores, with a higher score leading to a higher chance of being selected. The size of the population was set to 30 solutions after preliminary testing. Per generation, 30 crossovers are performed. From the 60 solutions (30 from the old population and 30 offspring), the 10 best solutions plus the 20 most diverse offspring constitute the next generation of the population. In the computational experiments below, this metaheuristic solution approach is stopped after 30 generations.

**Savings potential.** The best solution from the final generation of the population is returned as the final solution. This solution gives us the optimized total cost rate for a supplier \( s \in S \) or for a coalition of suppliers \( C \). The savings of any coalition \( C \) is determined by the difference between the total cost rate of the coalition and the cumulative stand-alone cost rate of all suppliers in the coalition. In our results, we will often express savings as a percentage of the cumulative stand-alone cost rate to have a more relative measure of savings.

A distinction can be made between a coalition of one supplier and a coalition containing multiple suppliers. If only a single supplier outsources its distribution activities to the LSP, then any savings are not the consequence of horizontal collaboration among suppliers, but are created by the fact that the LSP may operate more cost-efficiently than the supplier. On the other hand, if multiple suppliers outsource their activities to the LSP, the savings are not necessarily a consequence of the higher efficiency of the LSP, but also of the increased efficiency due to the horizontal collaboration among the suppliers. The LSP may or may not be more efficient in itself, but it can use the geographical proximity of the different retailer sets to design more cost-efficient routes and centralize the inventory.

Note that if the savings would be smaller than zero, coalition \( C \) will not be formed by the suppliers or the LSP since it does not generate benefits that can be shared among the partners.

4. **Illustrative example.** To illustrate the model and the savings calculations, an example was developed. It includes three suppliers, all active in the same geographical area and each serving their own set of 10 retailers. The location of the suppliers and their retailers, as well as the LSP, is shown in Figure 1. The locations of the
suppliers and the LSP are shown by the triangle in the middle of the geographical area. However, note that the suppliers and LSP are located very close to each other, but that their exact locations are not identical. In this example, every retailer is replenished by only one supplier. The daily demand rates of the retailers and other input data are specified in Table 1. All costs are expressed in euro. The solution algorithm is applied for each individual supplier and for the $7(= 2^3 - 1)$ possible (non-empty) coalitions via the LSP.

![Figure 1. Location of LSP, suppliers and retailers in the illustrative example](image)

| LSP & Suppliers | Retailers |
|-----------------|-----------|
| $\tau$          | $1.2$/km  |
| $\varphi_0$     | 20/tour   |
| $\kappa$        | 100 units |
| $\eta_j$        | 0.8/unit/day |
| $\varphi_j$     | 10/visit  |
| $\kappa_j$      | 100 units |

Table 1. Input data for the illustrative example

The routes for all individual suppliers and all coalitions and the resulting costs are determined using the CIRP metaheuristic described in Section 3. E.g., the routes for supplier 1 individually are displayed in Table 2 and the routes for the LSP when serving the grand coalition $\{1,2,3\}$ are listed in Table 3. The three retailer sets, each containing 10 retailers, are then merged into a retailer set with thirty retailers. By merging the retailer sets and serving them all from the same central LSP warehouse, the LSP can create more cost-efficient routes.

| $r$ | route                      | $T_r$ | $TC_r$ |
|-----|----------------------------|-------|--------|
| 1   | $S_1 - 6 - 5 - 1 - 2 - S_1$ | 6     | 152.41 |
| 2   | $S_1 - 3 - 8 - S_1$         | 5     | 72.62  |
| 3   | $S_1 - 7 - 9 - 10 - 4 - S_1$| 7     | 182.47 |

Table 2. Routes for supplier 1 individually
Table 3. Routes for the LSP in the grand coalition \{1,2,3\}

| Coalition | Cumulative individual cost | Coalition cost | Saving | %Saving |
|-----------|---------------------------|---------------|--------|---------|
| 1         | 407.50                    | -             | -      | -       |
| 2         | 310.22                    | -             | -      | -       |
| 3         | 417.75                    | -             | -      | -       |
| \{1\}     | 407.50                    | 410.20        | -2.70  | -0.66   |
| \{2\}     | 310.22                    | 310.01        | 0.21   | 0.07    |
| \{3\}     | 417.75                    | 428.84        | -11.09 | -2.65   |
| \{1,2\}  | 717.72                    | 659.96        | 57.76  | 8.05    |
| \{1,3\}  | 825.25                    | 780.96        | 44.29  | 5.3     |
| \{2,3\}  | 727.97                    | 697.86        | 30.11  | 4.14    |
| \{1,2,3\}| 1135.47                   | 1028.87       | 106.6  | 9.39    |

Table 4. Costs and savings individual suppliers and coalitions

5. **Computational results.** This section illustrates the savings potential that horizontal collaboration creates for various suppliers operating under VMI. Given that the vertical collaboration is inherent in the VMI, the savings analysis itself only comprises the impact of the horizontal collaboration among the suppliers and the LSP. The impact of the collaboration is quantified by applying the solution approach presented above on a set of problem instances in a design of experiments. The metaheuristic solution method is implemented in MS Visual C++ 2015. The results of the statistical analyses below are obtained with SPSS Statistics 25.

5.1. **Baseline results without collaboration.** To evaluate the solution approach and assess the savings potential of collaboration, tests were run on a set of newly generated problem instances. The design of experiments is inspired by that of Raa and Aghezzaf ([19]), which needed some adjustments to be suitable for the extended problem studied in this work. Firstly, multiple suppliers need to be included in a
single test instance such that horizontal collaboration among them can be introduced. Secondly, an LSP through which the suppliers can collaborate needs to be introduced.

Ten ‘small’ and ten ‘large’ datasets from the set of Raa and Aghezzaf ([19]) are used a starting point for our experiments. These instances were also used for benchmarking experiments by Chitsaz et al. ([6]) and by Raa and Dullaert ([20]). Each of these instances is used to represent a single supplier in our experiments. The service area of each supplier is a circle with a radius between 50 and 70 km. A supplier’s depot is located at the center of this circle and its retailer locations are scattered across the circular service area. The number of retailers per supplier is between 30 and 70 for the ten small instances, and between 80 and 120 for the ten large instances. Euclidean distances are used between the LSP, suppliers and retailers. The daily demand rates of the retailers are between 0.2 and 10 units/day and the retailers’ maximum storage capacities $\kappa_j$ are between 10 and 100 units. Making a delivery at a retailer takes 15 minutes and costs 10 euro ($\phi_j = 10$). The retailers’ inventory holding cost $\eta_j$ is 0.8 euro per unit per day ($\eta_j = 0.8$). The vehicles have a loading capacity $\kappa$ of 100 units and incur a travel cost of 1.2 euro per km ($\tau = 1.2$). Loading a vehicle is assumed to take half an hour and costs 20 euro ($\phi_0 = 20$).

Table 5 shows the daily total cost rates when the CIRP is solved for each of the suppliers individually, and the decomposition in distribution and holding cost rates. These are the baseline results against which outsourcing to the LSP and collaboration among multiple suppliers will be evaluated.

| Supplier | nrRet | Total | Distribution | Holding |
|----------|-------|-------|--------------|---------|
| S0       | 32    | 620.7 | 447.7        | 173.0   |
| S1       | 52    | 846.4 | 581.4        | 265.0   |
| S2       | 44    | 751.4 | 516.3        | 235.1   |
| S3       | 53    | 973.2 | 708.4        | 264.8   |
| S4       | 46    | 779.8 | 552.7        | 227.0   |
| S5       | 68    | 1255.6| 904.3        | 351.4   |
| S6       | 63    | 998.2 | 692.7        | 305.5   |
| S7       | 31    | 521.5 | 368.3        | 153.2   |
| S8       | 51    | 840.4 | 598.2        | 242.2   |
| S9       | 56    | 1058.9| 758.7        | 300.2   |
| L0       | 84    | 1491.4| 1061.3       | 430.1   |
| L1       | 111   | 1886.6| 1336.4       | 550.2   |
| L2       | 118   | 1900.0| 1279.1       | 620.9   |
| L3       | 82    | 1257.8| 843.9        | 413.8   |
| L4       | 94    | 1662.8| 1167.9       | 494.9   |
| L5       | 120   | 1831.3| 1249.8       | 581.5   |
| L6       | 99    | 1639.2| 1148.8       | 490.5   |
| L7       | 109   | 1838.5| 1296.7       | 541.8   |
| L8       | 86    | 1546.4| 1125.9       | 420.5   |
| L9       | 87    | 1405.8| 945.3        | 460.5   |

| Avg.     | 74.3  | 1255.3| 879.2        | 376.1   |

Table 5. Cost rates (in € per day) for the individual supplier instances
5.2. Factors design of experiments. A thorough evaluation of how the savings potential of the horizontal collaboration (using the relative measure of percentage savings) is impacted by three cost and network structure factors is performed in the design of experiments. The considered factors are discussed here in more detail.

5.2.1. LSP cost efficiency. The first factor for which we want to study its impact on the results is the cost efficiency of the LSP. This factor will be denoted $\text{costLSP}$. The costs that could be different for the LSP are those related to the distribution, i.e., the travel cost $\tau$, the loading cost $\varphi_0$, and the service cost $\varphi_j$. The inventory holding costs $\eta_j$ do not change. We express the cost efficiency of the LSP as percentage relative to the suppliers’ own costs and consider four levels of this factor, namely 90%, 95%, 100% and 105%.

The impact of $\text{costLSP}$ on the cost rates for the suppliers outsourcing to the LSP individually is displayed in Table 6, assuming that the LSP organises distribution from the supplier’s depot (at the center of its service area). Of course, when $\text{costLSP} = 100\%$, this corresponds to the baseline results of Table 5. Apart from the absolute cost rates, Table 6 also shows the relative cost rates compared to the baseline results. It can be observed that varying the distribution cost parameters leads to different solutions by making a different trade-off between distribution and holding costs. E.g., when distribution costs are lower, more frequent deliveries can be made which decreases holding costs.

| $\text{costLSP}$ | Total | Relative | Distribution | Relative | Holding | Relative |
|------------------|-------|----------|--------------|----------|---------|----------|
| 90%              | 1166.6| 0.93     | 800.2        | 0.91     | 366.4   | 0.97     |
| 95%              | 1211.2| 0.96     | 839.3        | 0.95     | 371.9   | 0.99     |
| 100%             | 1255.3| 1        | 879.2        | 1        | 376.1   | 1        |
| 105%             | 1300.0| 1.04     | 913.1        | 1.04     | 386.9   | 1.03     |

Table 6. Impact of $\text{costLSP}$ for the individual suppliers

5.2.2. Location of the LSP and supplier depots. The second factor we want to evaluate, is the location of the LSP depot relative to the supplier depots. For the results of Table 6, it was assumed that the distribution was done by the LSP, but still from the supplier depot. Put differently, we assumed that the LSP depot is in the same location as the supplier’s depot, in the center of the supplier’s service area. In many cases, this assumption does not hold, so we also need to consider the situation where the LSP depot is in a different location.

To this end, we considered a large circle with a radius of 110 km that represents the overall geographical area in which all suppliers and their retailers are located. The LSP depot is located at the center of this circle. For the previous results, the service areas of the suppliers are all centered at the same point in the center of this larger circle. As an alternative, we shifted the 20 suppliers’ service areas around at random inside the larger circle. The LSP depot is then no longer located at the center of a supplier’s service area.

The individual instances (whose service areas are circles with a radius of 50 to 70 km) are all shifted randomly inside the larger overall circle. For every supplier $s$, a random vector is generated (with an angle between 0 and 360 degrees and a length between 0 and $110 - R_s$ with $R_s$ the radius of the service area of supplier $s$). The supplier $s$ and its customer set are then all shifted inside the large circle using that random vector. Figure 2 illustrates this for four instances. In the left plot,
the four service areas are centered at the same location, where also the LSP depot (in black) is. In the right plot, the four service areas have been shifted. E.g., the supplier indicated in light grey was shifted about 50 km under an angle of about 40 degrees.

![Figure 2. Illustration of the factor overlap](image)

In our further experiments below, where we consider coalitions of multiple suppliers collaborating through the LSP, this factor will also be very important. In the first case (left part of Figure 2), the service areas of different suppliers overlap completely, whereas in the second case (right part of Figure 2), this is no longer true. The service areas of different suppliers can then still overlap a lot if they happen to be shifted towards the same zone in the larger circle, but the overlap can also be very small if they happen to be shifted towards different zones in the larger circle. For this reason, we will refer to this relative location of LSP and supplier depots as the factor overlap. This factor thus has two levels, 1 referring to the complete overlap situation and 0 to the situation with reduced overlap.

The impact of overlap on the cost rates for the suppliers outsourcing to the LSP individually is displayed in Table 7, when cost\textsubscript{LSP} = 100%. As can be expected, cost rates increase when the LSP depot from which retailers are supplied is not centrally located. Again, this does not just affect the distribution costs, but it leads to different solutions that have a different trade-off between distribution and holding costs.

| overlap | Total | Relative | Distribution | Relative | Holding | Relative |
|---------|-------|----------|--------------|----------|--------|----------|
| 1       | 1255.3| 1        | 879.2        | 1        | 376.1  | 1        |
| 0       | 1424.7| 1.13     | 1041.3       | 1.18     | 383.5  | 1.02     |

**Table 7. Impact of overlap for the individual suppliers**

5.2.3. **Coalition size.** The third and final factor to be evaluated, is the horizontal collaboration among suppliers. The number of suppliers in the coalition, denoted \( nr \), ranges from 1 to 8. \( nr = 1 \) represents the situation where a single supplier outsources its distribution to the LSP, as in the above results, while \( nr > 1 \) represents an actual horizontal collaboration of multiple suppliers.
Table 8. Illustration of the effect of \( nr \)

| \( nr \) | Coalition  | Total   | Cumulative | Saving | \%sav |
|--------|------------|---------|------------|--------|-------|
| 1      | S3         | 973.2   | 973.2      | 0      | 0.00  |
| 2      | S3-L8      | 2409.6  | 2519.6     | 110.1  | 4.37  |
| 3      | S3-L8-S2   | 3004.4  | 3271.0     | 266.6  | 8.15  |
| 4      | S3-L8-S2-L6| 4501.4  | 4910.2     | 408.9  | 8.33  |
| 5      | S3-L8-S2-L6-L3| 5620.9 | 6168.0     | 547.1  | 8.87  |
| 6      | S3-L8-S2-L6-L3-L1| 7248.3 | 8054.6     | 806.4  | 10.01 |
| 7      | S3-L8-S2-L6-L3-L1-S5| 8354.2 | 9310.2     | 956.0  | 10.27 |
| 8      | S3-L8-S2-L6-L3-L1-S5-L4| 9790.9 | 10973.1    | 1182.2 | 10.77 |

In our experiments, a coalition is generated by creating a random permutation of the set of suppliers. The CIRP is then solved for the coalition of the first 2 suppliers in the permutation, then the first 3, and so on, until the coalition reaches size 8. Table 8 shows the results for the permutation \{S3, L8, S2, L6, L3, L1, S5, L4\}, when \( costLSP = 1 \) and \( overlap = 1 \). The third column displays the cost rate of the CIRP solution for the coalition, while the fourth column shows the cumulative cost rate of the individual CIRP solutions. The difference between these two is the saving that can be created by the (horizontal) collaboration. This saving is also displayed as a percentage saving relative to the cumulative individual cost rates (i.e., the total cost rate without the LSP). The example of Table 8 shows that the savings potential increases with the number of suppliers in the coalition.

5.3. Collaborative results design of experiments. For every combination of levels of the factors \( overlap \) and \( costLSP \), a series of 20 supplier coalitions is generated using the random permutations. As such, we have a full factorial design of experiments with three factors and 20 replications, resulting in a total of 1,280 CIRP instances being solved.

The results across all instances with varying factor levels in the design of experiments show that savings can indeed be achieved through joint horizontal and vertical collaboration in transportation and inventory between an LSP and suppliers. However, the range of the savings across the instances is very broad and the savings are negative in many instances. Therefore, a more detailed analysis is done in an Analysis of Variance (ANOVA). In the ANOVA model, the three factors (\( overlap \), \( nr \), and \( costLSP \)) are included as categorical variables and the savings are expressed as percentages. The model evaluates the factors’ main effects as well as their interactions. The results of the ANOVA (Table 9) show that all factors have a significant impact on the savings as well as the two-way interactions involving \( overlap \). The interaction between \( nr \) and \( costLSP \) is not significant. The adjusted \( R^2 \) of the model is 93.8%. However, the differences in F-values and effect estimates indicate that the factors’ impacts have different orders of magnitude. According to the F-values, and as can be expected, the factor \( overlap \) has a very strong impact on the savings. \( costLSP \) also has a very considerable impact. Relative to the others, the impact of \( nr \) on the savings is rather small. A more detailed analysis of the results for each of the factors and the significant interactions is given in the next paragraphs.

Main effects. The factor with the largest impact is \( overlap \). Figure 3 shows the boxplot of the percentage savings for both levels of this factor, while Table 10 shows the average percentage savings.
Table 9. Results of the ANOVA with main effects and two-way interactions

```
| Source         | Type III Sum of Squares | df | Mean Square | F     | Sig.  |
|----------------|-------------------------|----|-------------|-------|-------|
| Corrected Model| 121661.580              | 21 | 5793.109    | 918.996 | 0.000 |
| Intercept      | 570.029                 | 1  | 570.029     | 90.422 | 0.000 |
| overlap        | 91248.526               | 1  | 91248.526   | 14474.561 | 0.000 |
| costLSP        | 20639.711               | 3  | 6879.904    | 1091.345 | 0.000 |
| nr             | 8779.363                | 7  | 1254.195    | 198.950 | 0.000 |
| overlap * costLSP | 306.054                | 3  | 102.018     | 16.183 | 0.000 |
| overlap * nr   | 687.925                 | 7  | 98.275      | 15.589 | 0.000 |
| Error          | 7930.510                | 1258 | 6.304       |       |       |
| Total          | 130162.118              | 1280 |             |       |       |
| Corrected Total| 129592.089              | 1279 |             |       |       |
```

*R Squared = 0.939 (Adjusted R Squared = 0.938).

Table 10. Average percentage savings for the different overlap levels

```
| overlap | Estimate |
|---------|----------|
| 0       | -7.8%    |
| 1       | 9.1%     |
```

We can conclude that the savings potential becomes smaller as the level of overlap between the suppliers’ customer zones decreases (without overlap, there is 16.9% less savings potential than with overlap). In fact, when there is limited overlap, Figure 3 and Table 10 show that the average savings potential is actually negative, or in other words, the suppliers are better off doing their distribution themselves instead of through the central LSP. Of course, this also depends on the cost levels, as discussed below in the interaction effects.
The factor with the second largest impact is costLSP. Figure 4 shows the boxplot of the percentage savings for the various levels of this factor. Table 11 shows the average savings for the different levels of this factor. Contrast statements confirmed that the average savings in all levels are all significantly different from each other.

\[
\begin{array}{c|cccc}
\text{costLSP} & 90\% & 95\% & 100\% & 105\% \\
\hline
\text{Estimate} & 6.1\% & 2.3\% & -1.0\% & -4.8\%
\end{array}
\]

Table 11. Average percentage savings for the different costLsp levels

Figure 4 and Table 11 thus confirm what we would obviously expect: the lower the LSP’s costs, the higher the supply chain savings. E.g. when cost levels of the LSP are at 90%, there is 7.1% more savings potential than when cost levels are the same for the LSP and the suppliers. However, when the LSP’s costs equal the costs of the suppliers, the average savings is negative (-1.0%), which indicates that the other factors need to be beneficial to be able to create savings.

Finally, the ANOVA also indicates that the factor nr has a significant effect on savings. Figure 5 shows the boxplot of the percentage savings for the various levels of this factor. Table 12 shows the average savings for the different levels of this factor.

\[
\begin{array}{c|cccccccc}
\text{nr} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
\text{Estimate} & -4.8\% & -1.8\% & -0.1\% & 1.0\% & 1.9\% & 2.5\% & 3.0\% & 3.5\%
\end{array}
\]

Table 12. Average percentage savings for the different nr levels

We can observe that the savings potential increases with the number of suppliers in the coalition. However, the difference in average savings of two subsequent
levels of \( nr \) becomes smaller as \( nr \) increases, indicating that the positive effect of adding an additional supplier to a coalition decreases with the coalition size (i.e., the law of diminishing returns applies). A post-hoc Tukey test performed all pairwise comparisons of the mean savings in all levels of \( nr \) to check whether they are all significantly different from each other. The output in Table 13 illustrates that as \( nr \) increases (\( nr > 4 \)), the difference in mean savings between consecutive levels becomes so small that it is no longer statistically significant.

![Boxplots of percentage savings for different levels of \( nr \)](image)

**Table 13.** Post-hoc Tukey test for \( nr \)

| \( nr \) | N  | 1       | 2       | 3       | 4       | 5       | 6       | 7       |
|---------|----|---------|---------|---------|---------|---------|---------|---------|
| 1       | 160| -4.7630 |         |         |         |         |         |         |
| 2       | 160| -1.7617 |         |         |         |         |         |         |
| 3       | 160| -0.1306 |         |         |         |         |         |         |
| 4       | 160| 1.0208  |         |         |         |         |         |         |
| 5       | 160| 1.8715  | 1.8715  |         |         |         |         |         |
| 6       | 160| 2.5444  | 2.5444  |         |         |         |         |         |
| 7       | 160| 3.0449  | 3.0449  |         |         |         |         |         |
| 8       | 160| 3.5125  |         |         |         |         |         |         |

| Sig.    |     | 1.000  | 1.000  | 1.000  | 0.051  | 0.244  | 0.632  | 0.710  |

\( ^a \) Means for groups in homogeneous subsets are displayed. Based on observed means. The error term is Mean Square(error) = 6.304

\( ^b \) Uses Harmonic Mean Sample Size = 160.000

\( ^c \) Alpha = 0.05
Interaction effects. Above, we already illustrated how the savings potential of horizontal collaboration through the LSP decreases (i) when the level of overlap between the suppliers’ customer zones is smaller, and (ii) when the LSP cost level increases. The significant interaction effect between the two factors, overlap and costLSP, furthermore indicates that these two effects reinforce each other. This can be observed in Figure 6. For both levels of factor overlap, the savings potential decreases as the level of costLSP increases, but this reduction is stronger when there is less overlap (overlap = 0).

Above, we found that, on average, the savings potential increases significantly with the number of suppliers. However, this is also significantly affected by the factor overlap. Figure 7 shows the interaction effect between the factors overlap and nr. When there is a lot of overlap (overlap = 1), the intuitively expected behavior is observed, i.e., there is a lot of savings potential, increasing with every additional supplier, but the additional savings decrease. When there is less overlap (overlap = 0), however, the results are different. In that situation, collaboration through the central LSP is not beneficial and therefore the savings potential is negative. Adding more suppliers does not make up for this.

Figure 8 shows the interaction effect between nr and costLSP. This illustrates that the increase of the savings potential increases with the number of suppliers shows a very similar curve for the different levels of costLSP, which is confirmed by the fact that this interaction is not statistically significant.

6. Conclusions. This paper presents a study that analyses the savings potential of combined horizontal and vertical collaboration in a distribution logistics network. Vertical collaboration is introduced through Vendor Managed Inventory. Horizontal collaboration is incorporated by forming coalitions among suppliers through an LSP. The resulting problem for which a metaheuristic solution method is presented,
is the Cyclic Inventory Routing Problem with constant retailer demand rates. In the savings calculations, the individual suppliers’ costs are compared to the suppliers coalitions’ costs. Computational experiments are performed to evaluate the savings potential of the solution approach. Although the solution approach includes both vertical and horizontal collaboration, the savings analysis only considers the horizontal collaboration since the vertical collaboration is inherent in the adoption
of VMI by the suppliers and their retailers. A design of experiments taking into consideration three factors (geographical overlap, cost-efficiency of the LSP compared to the suppliers, and the number of suppliers in a coalition) and their interaction effects is performed to evaluate their impact on the savings.

The computational results reveal that the horizontal collaboration does indeed have savings potential that can be realized using the presented solution approach. However, the statistical analyses performed on the generated savings reveal that the savings depend heavily on the levels of the three factors. The LSP’s cost-efficiency and the geographical overlap have the highest impact. The higher the LSP’s cost-efficiency and the higher the geographical overlap, the higher the savings. At least one of these factors needs to be beneficial for the LSP to be able to create savings. If the LSP costs are the same as the suppliers’ costs or worse, the savings potential is very low and the other factors need to be beneficial to still be able to create savings, i.e., the geographical overlap should be high and the number of suppliers participating in the coalitions should also be high. As the LSP’s cost-efficiency increases, the other factors become less important for the savings potential.

Although the savings potential is high when the overlap is high, the LSP’s cost-efficiency still matters, since the savings may turn out negative otherwise. However, the impact of the LSP’s cost-efficiency decreases as the overlap increases. Even though the number of suppliers is also significant, its impact on the savings is much smaller. Overall, a lower number of suppliers in a coalition results in lower savings. However, the impact of the number of suppliers depends heavily on the geographical overlap. When the overlap is small, a higher number of suppliers in a coalition might result in lower savings due to the geographical diffusion of the retailers.

The insights derived from our analyses can be useful for suppliers and LSPs that are considering horizontal collaboration as a means to reduce logistics costs. In this work, however, we analyzed the savings potential across all involved players in the supply chain. To be able to implement the collaboration in practice, the savings need to be distributed across the different players. This means that, when there is a savings potential, allocation mechanisms have to be developed such that the LSP, the suppliers and the retailers all end up with individually lower costs then when they work independently. Otherwise, they would not join the collaboration and the savings potential will not be realized. These savings allocation mechanisms should align the coalition preferences of all players (i.e., the LSP and suppliers on one hand and the supplier and his retailers on the other hand) and divide the savings across them in a fair manner. Designing such allocation mechanisms through pricing and incentive schemes can be a challenging avenue for future research that complements this work.

Other interesting research topics which should be investigated in the future are other variants of the IRP including vertical and horizontal collaboration, e.g., with multiple depots or pick-up and delivery problems. Finally, insights from this and future research could result in rules-of-thumb and suggestions for collaborative setups that are easy to implement for companies.

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