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ORIGINAL PAPER

Application and evaluation of a cost apportionment approach for integrating tour planning aspects into applied location planning

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Abstract In this paper, aspects of tour planning are included approximately into location planning for a distribution network, using a cost apportionment approach. This approach can be used with little effort to solve problems involving up to 4,000 customers in acceptable computation time. The developed approach is analyzed and evaluated on test instances that are based partly on real distribution data. This is performed by comparing the results of the cost apportionment approach with those of a classical location planning which does not explicitly take into account aspects of tour planning.

Keywords Location planning · Location routing problem · LRP · Cost apportionment · Tour planning · Vehicle routing problem · VRP · P-median problem · PMP

1 Introduction

Transportation costs in a distribution network represent the largest share of total logistic costs in many industries. For example, it represents 50 % in the automotive industry and 46 % in the consumer goods and media industry [5]. The important planning problems in distribution logistics include the selection of depot locations (location planning problem) and supply of customers of the given depot locations (tour planning problem). In view of their complexity, these two problems are largely represented and solved in the literature and practice not simultaneously but as individual models. In the *location routing problem* (LRP), the two problems are considered together in order to take account of the interdependence between location and tour planning. The approximate solution methods for LRP reduce the problem to a location planning problem by integrating tour planning approximately into location planning.

The application of a simple approximate solution method, which can perform location planning for several thousand customers in acceptable computation time, and a detailed comparison of the obtained solutions, with the solutions of a classical location planning approach using logistics key figures, do not exist in the literature. This paper represents a contribution to close this gap.

The paper is structured as follows. The next section provides an overview of the underlying problems and solution methods in the literature that are important for the paper. Section 3 deals with the used cost apportionment approach and its integration into the location planning model. In Sect. 4, the planning approach to generate tour planning solutions out of the cost apportionment approach for evaluation is described. The analysis, illustration and interpretation of the test results are the topics of Sect. 5. Finally, conclusions are drawn in Sect. 6.

2 Relevant planning problems and solution methods in the literature

A discrete location planning model describes the problem related to selecting location candidates such that a given

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cost function is minimized. For logistical problems, the cost function evaluates the delivery costs of a given set of customers whose goods are to be handled across selected locations. In formulating a discrete location planning problem as a *p-median problem* (PMP), *p* locations must be selected, at which locations' fixed costs are not considered. The basic models and solution methods are described in Klose [7] and Current et al. [2]. In this paper, PMP is used for the modeling.

The planning of round tours in local traffic is represented in the literature as the *vehicle routing problem* (VRP), which is described as follows: for a fleet of identical vehicles based at a depot, VRP determines the cost-minimal tour plan so that a given quantity of customers is served and the capacities of the vehicles are not exceeded. The basic models and solution methods are presented in the works of Toth and Vigo [12] and Golden and Assad [3].

The *location routing problem* (LRP) formulates the combined location and tour planning problem. Nagy and Salhi [9] provide an overview of the current state of scientific research. Klose [6] divides the solution methods for LRP into integrated and approximate approaches. The integrated solution methods connect a specific location planning model with a specific tour planning model, where the location problem is mostly the master problem and the tour planning problem is solved as a sub-problem for the regarded location configuration.

Following Bruns [1], Nagy and Salhi [9] define LRP as "location planning with tour planning aspects taken into account", which is reflected in the approximate solution methods for LRP. In these solution methods, tour planning is not explicitly conducted, but the delivery costs of a customer who is on a tour with several stops are estimated and included in location planning. Klose [6], Hirsch [4], and Bruns [1] give detailed explanations and references to the further literature. The approximate methods are basically divided into three approaches: cost regression, customer grouping, and cost apportionment.

In cost regression, a functional relationship between empirical tour costs and selected influencing factors is determined using a multiple regression. Regression coefficients for the cost function of location planning are derived from this.

In the process of customer grouping, a grouping of customers using logistical assumptions takes place with the help of hierarchical agglomerative clustering methods. For each cluster, the tour costs are determined or estimated and distributed between the tour customers. The cost per customer is an input for the cost function of location planning.

The basis of cost apportionment is a simple tour model, in which three cost components are expected on a tour: distance from the depot to the first customer and from the final customer to the depot (stem distance), distance from the first customer to the last customer (variable running distance), and service time at the customer. Using appropriate estimates for the single components, the tour costs are estimated and apportioned between the customers of a tour.

3 The used cost apportionment approach and its integration into location planning

In this section, the used cost apportionment approach and its integration into the location planning model is described.

The integration is realized by a modified cost function in the location planning model. This cost function contains the estimation of the delivery costs through the cost apportionment approach. In order to analyse and evaluate the cost apportionment approach, the classical location planning solution S^{classic} is calculated besides the location planning solution S^{tour} emerging from the cost apportionment approach (see Sects. 4, 5). The two associated location planning models represent a PMP.

In the classical location planning model $\text{PMP}^{\text{classic}}$, following cost function is used:

$$\min \sum_{i \in I} \sum_{j \in J} (b_i d_{ij}) z_{ij}, \tag{1}$$

I is the set of all customers and J is the set of all location candidates. In this paper, all customers represent a potential depot location ($I = J$). The binary variable z_{ij} is equal to 1 if customer i is assigned to depot j, otherwise z_{ij} is equal to zero. The delivery costs of one customer are calculated by the distance d_{ij} between the customer i and supplying depot j (the closest) weighted with demand b_i.

In the location planning model PMP^{tour} from which the location planning solution S^{tour} is calculated, the only change to $\text{PMP}^{\text{classic}}$ is the following cost function:

$$\min \sum_{i \in I} \sum_{j \in J} \bar{c}_{ij} z_{ij} \tag{2}$$

This cost function contains the estimate $\bar{c}_{ij}$ of the delivery costs from the cost apportionment approach.

The used cost apportionment approach is taken from Klose and Tüshaus [8] with only small modifications. The following definitions apply:

b_i	demand of customer i (t)
$\bar{b}_i$	estimate of the average demand on a tour containing customer i (t)
$\bar{c}_{ij}$	estimate of the delivery costs of customer i by location j
d_i	average distance from customer i to the two nearest neighbors (km)

d_{ij}	distance of customer i to location j (km)
$\overline{m}_{ij}$	estimate of the number of stops by $\overline{m}_{ij}^{Q}$ and $\overline{m}_{ij}^{T_{\max}}$
$\overline{m}_{ij}^{Q}$	Q-based estimate of the number of stops of a tour in which customer i is supplied from depot j
$\overline{m}_{ij}^{T_{\max}}$	$T_{\max}$-based estimate of the number of stops of a tour in which customer i is supplied from depot j
N_i	a set consisting of customer i and the $(\overline{m}_{ij}^{T_{\max}} - 1)$ nearest neighbors of customer i
Q	vehicle capacity (t)
ST	service time per customer (min)
t_i	average travel time from customer i to the two nearest neighbors (min)
t_{ij}	travel time from customer i to location j (min)
$T_{\max}$	maximum tour duration (min)
ω_d	distance-dependent vehicle costs (€/km)
ω_t	time-dependent vehicle costs (€/min)

The required estimates $\overline{c}_{ij}$ are determined with the following calculations:

$$\overline{m}_{ij}^{T_{\max}} = \max\left\{1, \left[\frac{T_{\max} - 2t_{ij} + t_i}{t_i + \mathrm{ST}}\right]\right\} \tag{3}$$

$$\overline{b}_i = \frac{1}{|N_i|}\sum_{l \in N_i} b_l \tag{4}$$

$$\overline{m}_{ij}^{Q} = \frac{Q}{\overline{b}_i} \tag{5}$$

$$\overline{m}_{ij} = \min\left\{\overline{m}_{ij}^{Q}, \overline{m}_{ij}^{T_{\max}}\right\} \tag{6}$$

$$\overline{c}_{ij} = \left(\frac{2d_{ij} - d_i}{\overline{m}_{ij}} + d_i\right)\omega_d + \left(\frac{2t_{ij} - t_i}{\overline{m}_{ij}} + (t_i + \mathrm{ST})\right)\omega_t \tag{7}$$

The number of stops are estimated on the basis of the maximum tour duration in Eq. (3). This estimate arises from the transformation of inequality $T_{\max} \geq 2t_{ij} + (\overline{m}_{ij}^{T_{\max}} - 1)t_i + \overline{m}_{ij}^{T_{\max}}\mathrm{ST}$, where the right side of the inequality is an estimate of the tour duration. If the supply of only one customer exceeds the maximum tour duration $T_{\max}$ (this means $\overline{m}_{ij}^{T_{\max}} < 1$), then a number of stops less than 1 is avoided by setting $\overline{m}_{ij}^{T_{\max}} = 1$. In Eq. (4), the average demand on a tour containing customer i is estimated by the average demand of all customers from set N_i. This value is used in Eq. (5) to estimate the number of stops based on vehicle capacity. In Eq. (6), the minimum of the two number of stop estimates is selected because the lower value is binding. Finally, the delivery costs of one customer are estimated in Eq. (7). In this equation, the tour costs estimated under the assumption of a tour length of $2d_{ij} + (\overline{m}_{ij} - 1)d_i$ and a tour duration of $2t_{ij} + (\overline{m}_{ij} - 1)t_i + \overline{m}_{ij}\mathrm{ST}$ are divided by the number of estimated stops $\overline{m}_{ij}$.

4 Planning approach

The aim of the planning approach is to obtain tour planning solutions to analyse and evaluate the two location planning models $\mathrm{PMP}^{\mathrm{classic}}$ and $\mathrm{PMP}^{\mathrm{tour}}$ and therefore the cost apportionment approach. For the solution of the location planning and vehicle routing problems, existing solution methods are used. In Fig. 1, the planning approach is illustrated.

In the first step, the formulated location planning models $\mathrm{PMP}^{\mathrm{classic}}$ and $\mathrm{PMP}^{\mathrm{tour}}$ (see Sect. 3) are solved with the *fast interchange* heuristic of Whitaker [13]. Before the start of the heuristic, the values d_i and t_i are calculated, and a list containing all customers in ascending order of distance from customer i is made for the calculation of set N_i. This list is created per customer. After the application of the heuristic, the location planning solutions S^{classic} and S^{tour} are obtained.

With the resulting p depot locations and the customers assigned to each depot from the location planning solutions S^{classic} and S^{tour}, p VRPs are formulated with maximum tour duration $T_{\max}$, vehicle capacity Q, and service time ST, which is equal for all customers. This p VRPs are formulated from S^{classic} and S^{tour}, respectively. The set of the p VRPs are called $\mathrm{VRP}^{\mathrm{classic}}$ and $\mathrm{VRP}^{\mathrm{tour}}$. The cost function of the VRPs are defined as follows:

$$\min \sum_{i \in I}\sum_{j \in I}\sum_{k \in K}(\omega_d d_{ij} + \omega_t t_{ij})x_{ijk} \tag{8}$$

Set I contains all customers (every customer can also be a depot), and x_{ijk} is a binary variable which is equal to 1 if

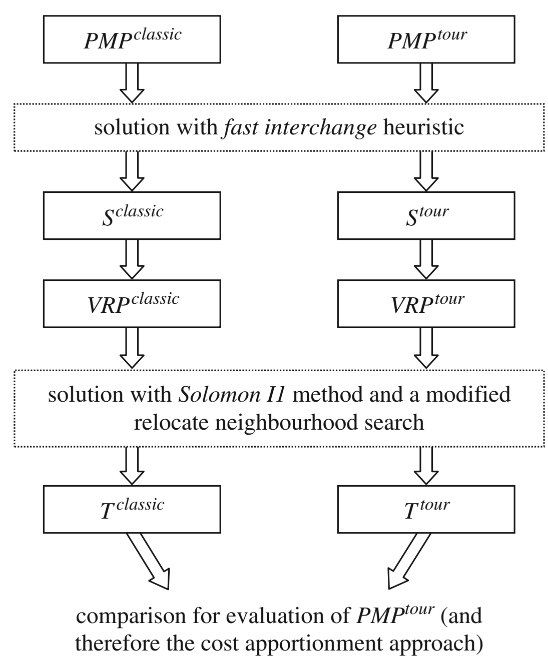

Fig. 1 Illustration of the planning approach

the vehicle $k \in K$ is driven directly from customer i to customer j. The maximum tour duration $T_{\max}$ can be exceeded if the supply of only one customer exceeds the maximum tour duration. On such a tour, there can be only one customer. The VRPs are solved with a heuristic consisting of the *Solomon I1* method [11] as an opening procedure and a modified relocate neighborhood search as an improvement method [10]. In every iteration of the improvement method, the objective function changes of all possible relocations are calculated and the best one is chosen. This is done until no relocation leads to a better solution. No 2-Opt or 3-Opt is conducted because the tour planning solutions are only used for the purpose of comparison of the two location planning models.

The generated solutions out of $\mathrm{VRP}^{\mathrm{classic}}$ and $\mathrm{VRP}^{\mathrm{tour}}$ are called T^{classic} and T^{tour}. A comparison of T^{classic} and T^{tour} evaluates the two different location planning models, $\mathrm{PMP}^{\mathrm{classic}}$ and $\mathrm{PMP}^{\mathrm{tour}}$. A detailed description of the analyzed tour planning key figures follows in Sect. 5.

5 Test results

5.1 Test instances and variants

Table 1 presents the six test instances (TI) used. Test instances TI 1 to TI 3 are generated using real distribution data. In the other test instances, the customer density in individual areas depends on their population density. In test instances TI 1 to TI 4 and TI 6, there are more or less strong differences in customer density (the strongest differences are in TI 1). However, the differences in customer density are small in TI 5 in comparison with the other test instances. The distances d_{ij} and travel times t_{ij} are taken from a digital road network. The demand quantities b_i are all between 0.5 tonnes and 2 tonnes general cargo.

An overview of the eight different test variants is listed in Table 2. A variant defines a parameter combination of vehicle capacity Q (t), maximum tour duration $T_{\max}$ (min), and service time ST (min). For each variant of a test instance, different values of p (number of depot locations) are considered. The values of p are identical for all variants within a test instance, but vary between the test instances according to its structure.

5.2 Illustration of test results

A comparison between the two location planning approaches is made, first with the following formula:

$$\Delta C = \frac{C(T^{\mathrm{classic}}) - C(T^{\mathrm{tour}})}{C(T^{\mathrm{classic}})} \qquad (9)$$

Table 1 Overview of test instances

Test instance	Distribution zone (area in [km^2/1,000])	Number of customers	Industry
TI 1	Germany (357)	2,333	Beverage
TI 2	South East Germany (139)	2,709	Food
TI 3	France (538)	1,692	Tire
TI 4	Germany (357)	2,496	–
TI 5	South Germany (117)	3,790	–
TI 6	North East Germany (184)	3,209	–

Table 2 Overview of test variants

Variant	Vehicle capacity Q (t)	Maximum tour duration $T_{\max}$ (min)	Service time ST (min)
1	10	480	30
2	15	480	30
3	10	480	15
4	15	480	15
5	10	360	30
6	15	360	30
7	10	360	15
8	15	360	15

Using (9), the relative change of the new tour costs $C(T^{\mathrm{tour}})$ in comparison with the previous tour costs $C(T^{\mathrm{classic}})$ is calculated. The service costs (number of customers · service time per customer · cost per time unit) are not included in $C(T^{\mathrm{classic}})$ and $C(T^{\mathrm{tour}})$ because they represent a fixed value which cannot be influenced by a modified location selection. Therefore, ΔC represents only the change in tour costs, which is influenced by optimization. Table 3 provides the number of the location planning solutions for each test instance where a cost reduction ($\Delta C > 0$) can be achieved using the cost apportionment approach. In addition, the table shows the average and maximum cost reduction. The same information is given according to cost increases ($\Delta C < 0$) in Table 4.

In test instances TI 1 to TI 3, the share of location solutions where there is a cost reduction lies between 95 and 99 %. This share is lower in TI 4 to TI 6 and lies between 79 and 85 %. The maximum cost reductions are quite high in all test instances except TI 5 and lie between 14.5 % in TI 6 and 22.9 % in TI 1. In TI 5, the maximum cost reduction is 3.6 %, which is relatively low. It is obvious that cost reductions are much more distinctive than cost increases. The average cost increase is always less than or equal to 1 %. The maximum cost increases in TI 1

Table 3 Cost reductions

Test instance	Number of cost reductions	Share (%)	ø Cost reduction (%)	Maximum cost reduction (%)
TI 1	148	97.4	8.2	22.9
TI 2	158	98.7	5.7	20.1
TI 3	76	95.0	7.8	17.2
TI 4	102	85.0	3.4	16.6
TI 5	99	82.5	1.7	3.6
TI 6	95	79.2	3.5	14.5

Table 4 Cost increases

Test instance	Number of cost increases	Share (%)	ø Cost increase (%)	Maximum cost increase (%)
TI 1	4	2.6	0.4	0.8
TI 2	2	1.3	0.1	0.2
TI 3	4	5.0	1.0	2.2
TI 4	18	15.0	0.7	2.2
TI 5	21	17.5	0.8	2.6
TI 6	25	20.8	0.5	2.2

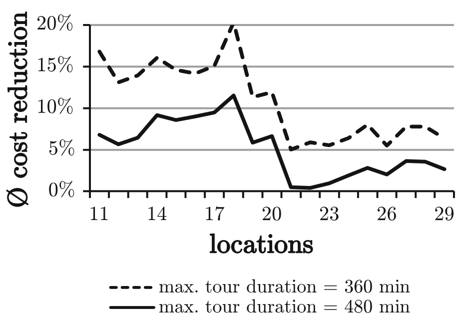

Fig. 2 Cost reduction TI 1

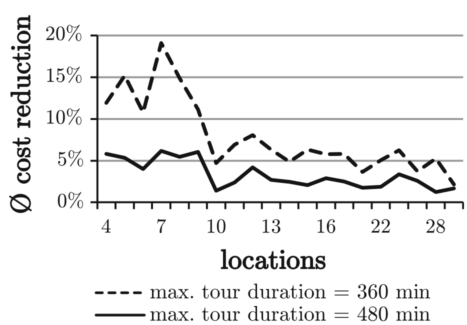

Fig. 3 Cost reduction TI 2

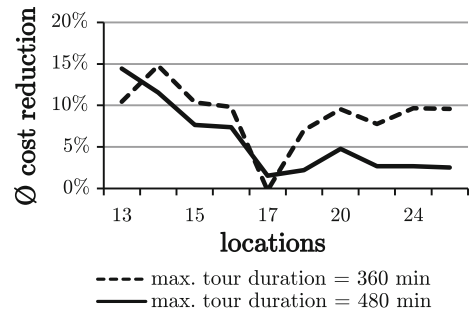

Fig. 4 Cost reduction TI 3

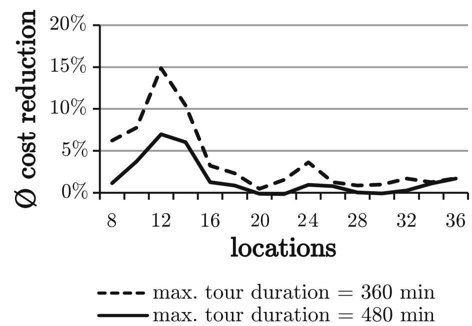

Fig. 5 Cost reduction TI 4

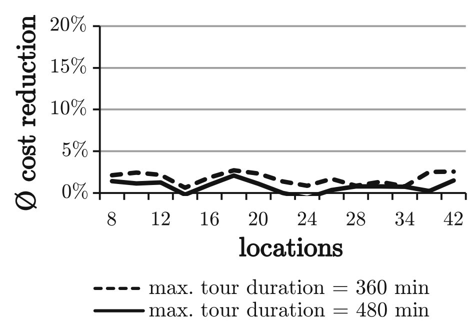

Fig. 6 Cost reduction TI 5

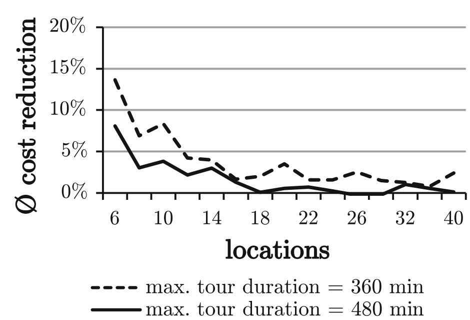

Fig. 7 Cost reduction TI 6

and TI 2 are 0.8 and 0.2 %, respectively. The maximum cost increases in TI 3 to TI 6 are a bit higher, but never greater than 2.6 %.

Figures 2, 3, 4, 5, 6 and 7 show the average cost reduction ΔC for all test instances of the two possible values of the maximum tour duration T_{max}, depending on the number of locations. For curve $T_{max} = 480$, the average ΔC of test variants 1–4, and for curve $T_{max} = 360$, the average ΔC of test variants 5–8, are used.

In all test instances except TI 5, cost reductions are highest when the number of locations is small and tend to decrease when the number of locations increases. The cost reductions in TI 5 are on a constant and relatively low level. The influence of the maximum tour duration on cost reduction is also obvious. An increase in the average cost reduction is observable in all test instances at a lower maximum tour duration. The cost reductions at $T_{\max} = 360$ are nearly twice as high as that at $T_{\max} = 480$. A comparison of the corresponding curves of vehicle capacity Q and service time ST shows no systematic influence on cost reduction ΔC to the extent such as the maximum tour duration.

Following key figures are used for further analysis:

cost_j	tour costs of depot j including service costs (€)
tours	number of tours of all depots
tours_j	number of tours of depot j
$\text{MAD}^{\text{tours}}$	mean absolute deviation (MAD) of tours_j
amount_j	handling amount of depot j (t)
$\text{MAD}^{\text{amount}}$	MAD of amount_j (t)
customers_j	number of customers to serve by depot j
$\text{MAD}^{\text{customers}}$	MAD of customers_j
$\text{AVG}^{\text{stops}}$	average number of stops of all tours
$\text{AVG}_j^{\text{stops}}$	average number of stops of tours of depot j
$\text{MAD}^{\text{stops}}$	MAD of number of stops of all tours
AVG^{cap}	average capacity utilization of all vehicles
$\text{AVG}_j^{\text{cap}}$	average capacity utilization of vehicles of depot j
MAD^{cap}	MAD of capacity utilization of all vehicles
AVG^{rel}	average of all depot-customer distances (km)
$\text{AVG}_j^{\text{rel}}$	average of all depot-customer distances of depot j (km)

Table 5 shows that in all test instances the number of tours tend to decrease in the event of a cost reduction. At the same time, there is an increase in the MAD of the number of tours and customers and the handling amount between the depots. The average number of stops of a tour and capacity utilization of vehicles tends to increase, whereas the MAD of these two key figures tends to decrease. The average distance between the depots and the assigned customers increases in all test instances in all or almost all solutions.

In the following, an example for three of the six test instances is presented, respectively. The number of depots and tour planning parameters used for the examples are shown in Table 6. The comparison of two different location planning solutions is based on a graphical comparison and on location and tour planning key figures (see above).

5.2.1 *Example 1*

In Example 1 (Tables 7, 8, 9; Fig. 8), there are 15 depots in the southern distribution area at S^{classic} (costs = 128,932€, customers = 2,182, tours = 232) and four depots in the northern distribution area (costs = 27,096€, customers = 151, tours = 41). At S^{tour}, however, there are only 13 depots in the south (costs = 128,223€, customers = 2,168, tours = 229), and the number of depots in the north rises to six (costs = 21,627€, customers = 165, tours = 33). By the location distribution in S^{tour}, it is possible to supply a nearly identical number of customers with the same costs and number of tours in the southern distribution area despite the reduction of two depots. The cost reduction ΔC of about 7.5 % and tour reduction of 4 % arise because the costs (including service costs) and number of tours in the northern distribution area (with a low customer density) decrease owing to the two additional locations by about 20 %. If you look at the northern and southern distribution areas separately, it becomes evident that the increase in $\text{AVG}^{\text{stops}}$ and AVG^{cap} by 4.2 % is caused by the northern distribution area. The average number of stops and capacity utilization of vehicles hardly ever changes in the southern distribution area ($\text{AVG}^{\text{stops}} = 9.75$ and $\text{AVG}^{\text{cap}} = 0.68$ at T^{classic}; $\text{AVG}^{\text{stops}} = 9.71$ and $\text{AVG}^{\text{Cap}} = 0.68$ at T^{tour}). In the northern distribution area, these two values increase significantly ($\text{AVG}^{\text{stops}} = 4.38$ and $\text{AVG}^{\text{cap}} = 0.29$ at T^{classic}; $\text{AVG}^{\text{stops}} = 5.36$ and $\text{AVG}^{\text{cap}} = 0.37$ at T^{tour}). The reduction of $\text{MAD}^{\text{stops}}$ and MAD^{cap} by about 15 % can be explained by this increases because there are less very small number of stops and capacity utilizations of vehicles. The average distance of all depot-customer relations AVG^{rel} increases by 9.5 %. Increases of the MAD of the number of tours and customers and the handling amount of the depots lie between 53 and 91 %. One explanation for this is that the number of tours and customers as well as the handling amount of the depots tend to be evenly lower in the north and higher in the south.

5.2.2 *Example 2*

In Example 2 (Tables 10, 11, 12; Fig. 9), only small shifts occur at the four depots in the northern distribution area (depots 1–4). These small shifts account for approximately 30 % of the total cost and tour reduction (costs=97,588€, customers = 1,105, and tours = 217 at T^{classic}; costs = 92,174€, customers = 1,102, and tours = 204 at T^{tour}). In the southern distribution area (depots 5–9), there are strong depot shifts. One depot is placed in the metropolitan area of Munich (depot 8), and the southern depots (depots 7 and 9) are moved toward the edges of the distribution area. The main part of the total cost and tour reduction as well as

Table 5 Change in tour planning key figures of T^{tour} compared to $T^{classic}$ (share in percentage of tour planning solutions which achieved a cost reduction)

Test instance (TI)	1	2	3	4	5	6
tours↓	98.7	93.7	97.4	89.2	85.9	86.3
MAD^{tours}↑	100	78.5	67.1	100	90.9	80.0
$MAD^{customers}$↑	100	82.9	90.8	99.0	97.0	89.5
MAD^{amount}↑	100	82.9	85.5	95.1	98.0	85.3
AVG^{stops}↑	93.2	88.6	96.1	85.3	76.8	80.0
MAD^{stops}↓	94.6	84.2	92.1	80.4	66.7	74.7
AVG^{cap}↑	93.9	89.2	97.4	87.3	77.8	81.1
MAD^{cap}↓	93.9	88.6	89.5	83.3	75.8	69.5
AVG^{rel}↑	100	100	97.4	100	100	99.0

Table 6 Number of depots and tour planning parameters of the examples

Example	Test instance	Number of depots	Vehicle capacity (t)	Max. tour duration (min)	Service time (min)
1	*TI* 1	19	15	480	30
2	*TI* 2	9	15	360	30
3	*TI* 3	16	15	480	15

the increased number of stops and capacity utilization of vehicles can be explained by these shifts (costs = 134,033€, customers = 1,604, tours = 302, AVG^{stops} = 5.36 and AVG^{cap} = 0.44 at $T^{classic}$; costs = 120,925€, customers = 1,607, tours = 278, AVG^{stops} = 5.80 and AVG^{cap} = 0.48 at T^{tour}). The presence of two large (5 and 8) and two small (7 and 9) depot areas at S^{tour} in comparison with $S^{classic}$ leads to an increase in MAD^{tours}, $MAD^{customers}$ and MAD^{amount}.

5.2.3 *Example 3*

In Example 3 (Tables 13, 14, 15; Fig. 10), the majority of depots show no shift or only a small shift. However, the distribution area with a low customer density (depots 10, 11, and 14) includes depot 8 at S^{tour} in addition, and as compensation for this, depot areas 7 and 8 (at $S^{classic}$) in the northeast are united as one depot area. A comparison of $T^{classic}$ and T^{tour} primarily shows improvements due to the addition of depot 8 in the distribution area with a low customer density (costs = 30,880€, customers = 237, tours = 44, AVG^{stops} = 5.58 and AVG^{cap} = 0.38 at $T^{classic}$; costs = 23,714€, customers = 254, tours = 36, AVG^{stops} = 7.22 and AVG^{cap} = 0.48 at T^{tour}). The remaining distribution area can be supplied at T^{tour} with one location less than at $T^{classic}$ with roughly the same tour planning key figures. Example 3 is very similar to Example 1. The explanation for the increase in $MAD^{customers}$ and MAD^{amount} and the decrease in MAD^{stops} and MAD^{cap} is the same as in Example 1.

5.2.4 *Summing up the examples*

Table 16 lists the percentage changes of the tour planning key figures from the examples. The course of the changes is consistent with the observations made for all solutions in which a cost reduction was achieved (see Table 5).

5.3 Interpretation of test results

The cost apportionment approach assumes that a customer with a greater distance from a depot causes the number of stops on a tour to decrease because the increased time required for the outward and return trip diminishes the time for stopping for further customers on this tour. Furthermore, an increase in the estimated value for the average distance between the customers on a tour leads to a reduction in the estimated number of stops. Therefore, the delivery costs for customers far away from the depot and located in an area with a low customer density can be divided between fewer customers. The delivery costs of such customers are evaluated through the cost apportionment approach as relatively “high”. These aspects are not considered in the classical location planning approach.

It has been observed that more depots tend to be located in areas with a low customer density in solutions based on the cost apportionment approach compared to the classical location planning approach (see Examples 1 and 3). Therefore, the depot areas that have a low customer density tend to be smaller in S^{tour} than in $S^{classic}$. In this way, it is possible to reduce the “expensive” customers on the edge of a large depot area having a low customer density and achieve significant cost and tour reductions.

A significant cost and tour reduction could be observed even in distribution areas where there is no strong difference in customer density. This could be achieved by avoiding a relatively even distribution of the depots over the distribution area in which there is a depot with a large metropolitan area on the edge (with many "expensive" customers; see Example 2).

These two observations are reflected in the increase in the MAD of the number of customers and tours as well as the handling amount between the depots. An increase of depots in areas with a low customer density and a decrease of depots in areas with a high customer density or an uneven distribution of depots lead to more extreme values.

Owing to an increase in the average number of stops and capacity utilization in the distribution areas in which these values are below the overall average and the constancy of these values in the remaining distribution area, there is a reduction in the MAD of these quantities.

Improvement of tour costs (see Figs. 2, 3, 4, 5, 6, 7) strongly depends on the maximum tour duration. A lower maximum tour duration leads to a decrease in the distance to customer areas where very few stops are possible because of the required time for the outward and return trip. Therefore, with a low maximum tour duration, more costs can be saved by reducing large depot areas through the cost apportionment approach because more "expensive" customers can be avoided.

Table 7 Parameter—Example 1

Test instance	TI 1
Number of depots	19
Vehicle capacity (t)	15
Max. tour duration (min)	480
Service time (min)	30
Cost per km (€)	0.78
Cost per min (€)	1.06
Service cost (€)	73,944

Table 8 Result summary—Example 1

Absolute cost reduction (€)	6,179
Relative cost reduction $\Delta C(\%)$	7.5
Relative cost reduction incl. service costs (%)	4.0
Absolute tour reduction	11
Relative tour reduction (%)	4.0

Table 9 Detailed comparison of S^{classic} (left columns) and S^{tour} (right columns)—Example 1

j (depot)	cost_j (€)		customers_j		tours_j		amount_j (t)		$\text{AVG}_j^{\text{stops}}$		$\text{AVG}_j^{\text{cap}}$		$\text{AVG}_j^{\text{rel}}$ (km)	
	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour
1	6,554	3,541	24	19	9	5	24.3	18.6	2.7	3.8	0.18	0.25	104.1	81.4
2	6,003	6,546	65	70	10	10	65.0	73.4	6.5	7.0	0.43	0.49	61.9	62.7
3	7,487	3,515	35	22	12	5	35.5	22.0	2.9	4.4	0.20	0.29	98.1	75.6
4	7,053	2,297	27	17	10	4	27.3	16.9	2.7	4.3	0.18	0.28	109.1	73.9
5	8,311	7,707	98	111	14	13	105.8	115.9	7.0	8.5	0.50	0.59	60.1	53.8
6	2,703	2,703	39	39	5	5	41.8	41.8	7.8	7.8	0.56	0.56	37.2	37.2
7	6,092	3,513	122	24	11	6	134.9	24.5	11.1	4.0	0.82	0.27	23.1	78.8
8	10,034	10,800	116	130	17	18	118.6	132.5	6.8	7.2	0.46	0.49	54.9	59.1
9	8,318	15,444	166	291	15	28	173.7	312.4	11.1	10.4	0.77	0.74	28.0	39.0
10	7,211	2,213	113	13	13	3	112.6	12.8	8.7	4.3	0.58	0.29	36.2	57.1
11	7,176	5,872	70	62	11	10	75.0	65.4	6.4	6.2	0.45	0.44	60.5	57.4
12	14,452	19,825	338	429	28	37	348.4	443.7	12.1	11.6	0.83	0.80	21.0	27.9
13	13,730	12,946	264	247	26	24	279.4	261.3	10.2	10.3	0.72	0.73	30.3	30.0
14	7,086	4,096	119	50	13	7	119.5	50.3	9.2	7.1	0.61	0.48	33.4	53.4
15	11,400	12,421	227	237	21	23	244.5	253.5	10.8	10.3	0.78	0.73	27.7	31.1
16	8,540	14,015	118	189	15	23	130.0	197.2	7.9	8.2	0.58	0.57	48.6	57.5
17	9,852	5,847	128	83	17	10	134.1	91.0	7.5	8.3	0.53	0.61	51.8	49.2
18	8,235	6,691	154	129	15	13	160.3	133.2	10.3	9.9	0.71	0.68	30.8	29.8
19	5,792	9,858	110	171	11	18	112.8	177.1	10.0	9.5	0.68	0.66	29.8	39.6
Sum	156,029	149,850	2,333	2,333	273	262	2,443.5	2,443.5	–	–	–	–	–	–
AVG	–	–	–	–	–	–	–	–	8.55	8.91	0.597	0.622	37.8	41.4
MAD	–	–	56.87	88.49	4.11	7.84	60.68	92.84	2.61	2.16	0.186	0.159	–	–

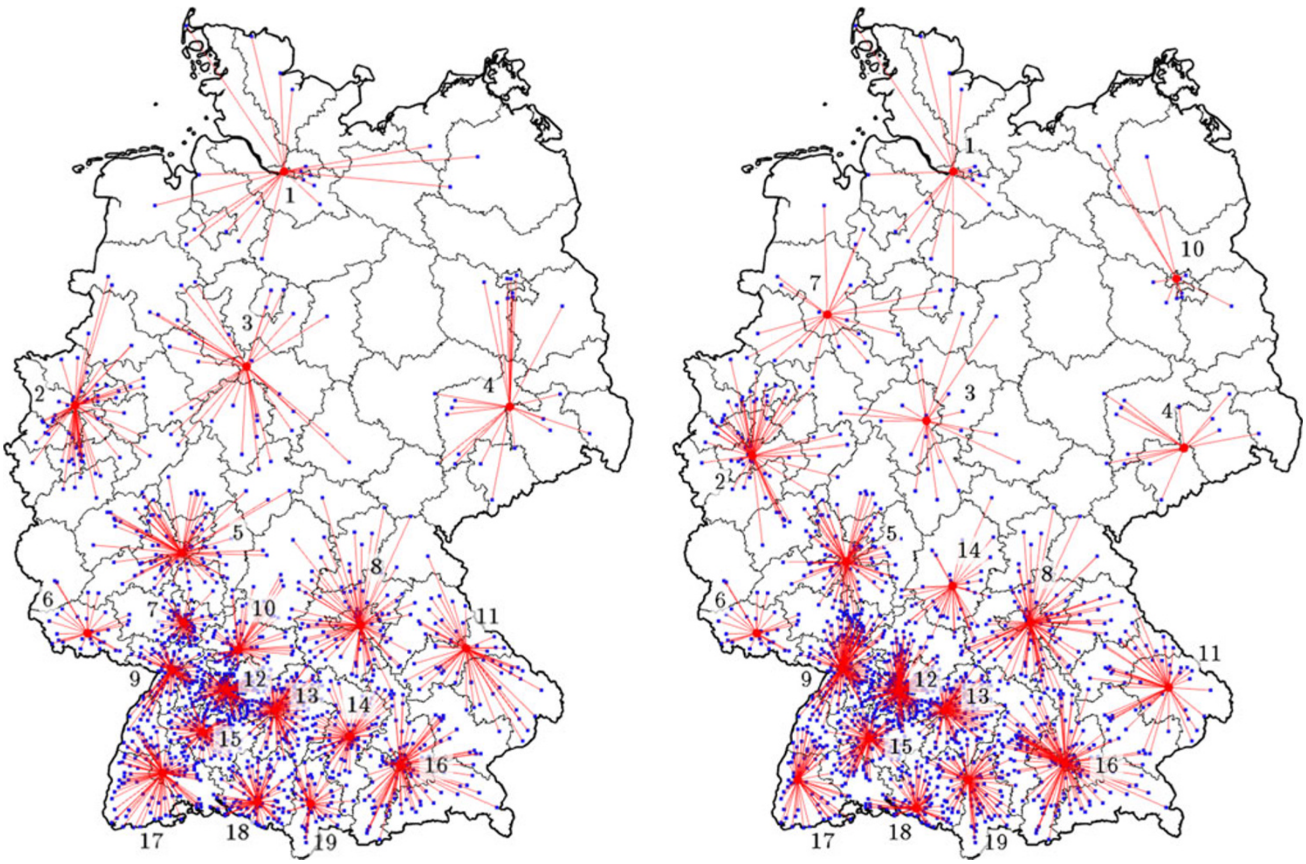

Fig. 8 Graphical comparison of location solutions (*left* S^{classic}, *right* S^{tour})—Example 1

Table 10 Parameter—Example 2

Test instance	Number of depots	Vehicle capacity (t)	Max. tour duration (min)	Service time (min)	cost per km (€)	cost per min (€)	service cost (€)
TI 2	9	15	360	30	0.78	1.06	85,862

Table 11 Detailed comparison of S^{classic} (left columns) and S^{tour} (right columns)—Example 2

j (depot)	$cost_j$ (€)		$customers_j$		$tours_j$		$amount_j$ (t)		AVG_j^{stops}		AVG_j^{cap}		AVG_j^{rel} (km)	
	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour
1	18,297	20,255	230	251	44	45	274.0	297.4	5.2	5.6	0.42	0.44	45.5	49.2
2	31,534	29,436	348	340	69	66	442.9	433.9	5.0	5.2	0.43	0.44	52.0	54.8
3	25,689	21,900	271	261	56	47	318.6	310.6	4.8	5.6	0.38	0.44	51.1	49.6
4	22,069	20,583	256	250	48	46	310.1	302.7	5.3	5.4	0.43	0.44	52.4	51.1
5	18,418	26,758	265	341	43	61	336.2	423.2	6.2	5.6	0.52	0.46	41.3	51.3
6	28,312	27,440	363	355	64	64	435.8	425.7	5.7	5.5	0.45	0.44	50.7	50.0
7	29,133	15,543	291	202	63	35	368.9	254.1	4.6	5.8	0.39	0.48	58.0	50.4
8	21,800	36,101	264	473	51	82	313.0	585.8	5.2	5.8	0.41	0.48	43.5	57.2
9	36,368	15,083	421	236	81	36	524.3	290.4	5.2	6.6	0.43	0.54	52.1	35.7
Sum	231,621	213,099	2,709	2,709	519	482	3,323.8	3,323.8	–	–	–	–	–	–
AVG	–	–	–	–	–	–	–	–	5.22	5.62	0.427	0.460	50.0	50.8
MAD	–	–	50.89	67.78	10.30	13.06	65.57	86.96	1.40	1.28	0.128	0.120	–	–

Table 12 Result summary—Example 2

Absolute cost reduction (€)	Relative cost reduction ΔC (%)	Relative cost reduction incl. service costs (%)	Absolute tour reduction	Relative tour reduction (%)
18,523	12.7	8.0	37	7.1

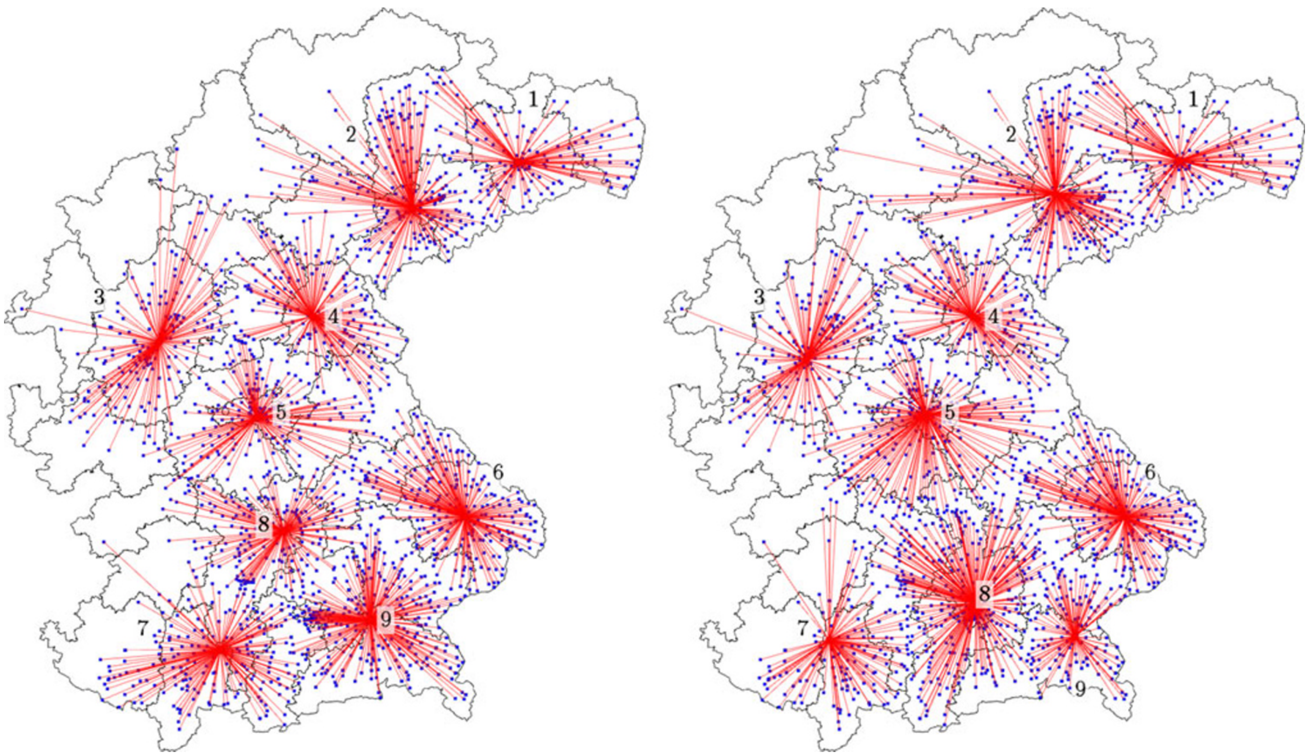

Fig. 9 Graphical comparison of location solutions (*left* S^{classic}, *right* S^{tour})—Example 2

Table 13 Parameter—Example 3

Test instance	Number of depots	Vehicle capacity (t)	Max. tour duration (min)	Service time (min)	Cost per km (€)	Cost per min (€)	Service cost (€)
*TI*3	16	15	480	15	0.78	1.06	26,814

The strong dependence of tour costs on the number of locations (see Figs. 2, 3, 4, 5, 6, 7) can be explained by the fact that when the number of depots increase, the average depot area decreases, and there tends to be even less very large depots areas. This decreases the possibility of cost reduction by avoiding "expensive" customers.

The differences of cost reduction between the test instances (see Table 3; Figs. 2, 3, 4, 5, 6, 7) can be explained by the difference in customer distribution. It is striking that high cost reductions could be achieved in test instances where there are more or less strong differences in customer density (test instances TI 1 to TI 4 and TI 6). In such test instances, it is more common (in the classical location planning approach) to involve comparatively large depot areas with "expensive" customers, or depot areas with large metropolitan areas on the edge of a depot area. This effect can be reduced or avoided by using the cost apportionment approach. Accordingly, the cost reductions at TI 5 compared to the other test instances are small.

6 Conclusion

In this paper, aspects of tour planning were integrated into location planning by a cost apportionment approach. This was done using a modified cost function in location planning. The required values for the cost apportionment approach were estimated using simple calculations. The computational effort was low. In this way, location planning can be done for up to 4,000 customers in less than 15 min of computation time. The application of this approach for a particular test instance is very easy because only the tour planning parameters need to be specified.

Table 14 Detailed comparison of S^{classic} (left columns) and S^{tour} (right columns)—Example 3

j (depot)	cost_j (€)		customers_j		tours_j		amount_j (t)		$\text{AVG}_j^{\text{stops}}$		$\text{AVG}_j^{\text{cap}}$		$\text{AVG}_j^{\text{rel}}$ (km)	
	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour	clas.	tour
1	7,818	8,488	135	139	12	13	133.6	137.4	11.3	10.7	0.74	0.70	66.7	70.5
2	7,978	8,178	89	92	12	13	90.4	93.7	7.4	7.1	0.50	0.48	85.6	86.3
3	5,445	3,953	66	51	8	6	69.7	55.5	8.3	8.5	0.58	0.62	82.9	79.3
4	18,112	17,930	343	341	31	31	338.0	338.1	11.1	11.0	0.73	0.73	49.1	52.4
5	8,107	8,537	106	115	12	13	108.3	118.2	8.8	8.8	0.60	0.61	76.5	82.9
6	9,284	7,272	88	79	15	11	87.1	76.8	5.9	7.2	0.39	0.47	96.1	89.5
7	4,857	9,464	68	120	8	14	69.7	119.4	8.5	8.6	0.58	0.57	61.8	95.5
8	5,140	5,672	74	52	8	9	73.1	51.0	9.3	5.8	0.61	0.38	67.1	81.6
9	7,868	9,850	72	87	11	14	75.5	90.3	6.5	6.2	0.46	0.43	90.2	103.8
10	7,299	5,965	55	56	10	9	56.3	56.6	5.5	6.2	0.38	0.42	89.1	86.4
11	15,654	6,213	99	72	22	9	98.6	70.3	4.5	8.0	0.30	0.52	99.7	74.9
12	15,054	15,693	190	194	22	23	186.7	191.0	8.6	8.4	0.57	0.55	83.5	85.9
13	4,004	3,785	50	48	7	6	43.9	41.8	7.1	8.0	0.42	0.46	62.7	62.3
14	7,926	5,864	83	74	12	9	84.2	77.2	6.9	8.2	0.47	0.57	71.9	60.9
15	7,673	5,352	77	59	11	8	72.8	55.1	7.0	7.4	0.44	0.46	80.6	72.6
16	6,948	8,229	97	113	10	12	90.8	106.3	9.7	9.4	0.61	0.59	80.7	84.3
Sum	139,168	130,444	1,692	1,692	211	200	1,678.7	1,678.7	–	–	–	–	–	–
AVG	–	–	–	–	–	–	–	–	8.02	8.46	0.530	0.560	73.8	76.4
MAD	–	–	43.88	48.44	4.66	4.19	43.36	47.62	2.94	2.61	0.207	0.180	–	–

Table 15 Result summary—Example 3

Absolute cost reduction (€)	Relative cost reduction ΔC (%)	Relative cost reduction incl. service costs (%)	Absolute tour reduction	Relative tour reduction (%)
8,723	7.8	6.3	11	5.2

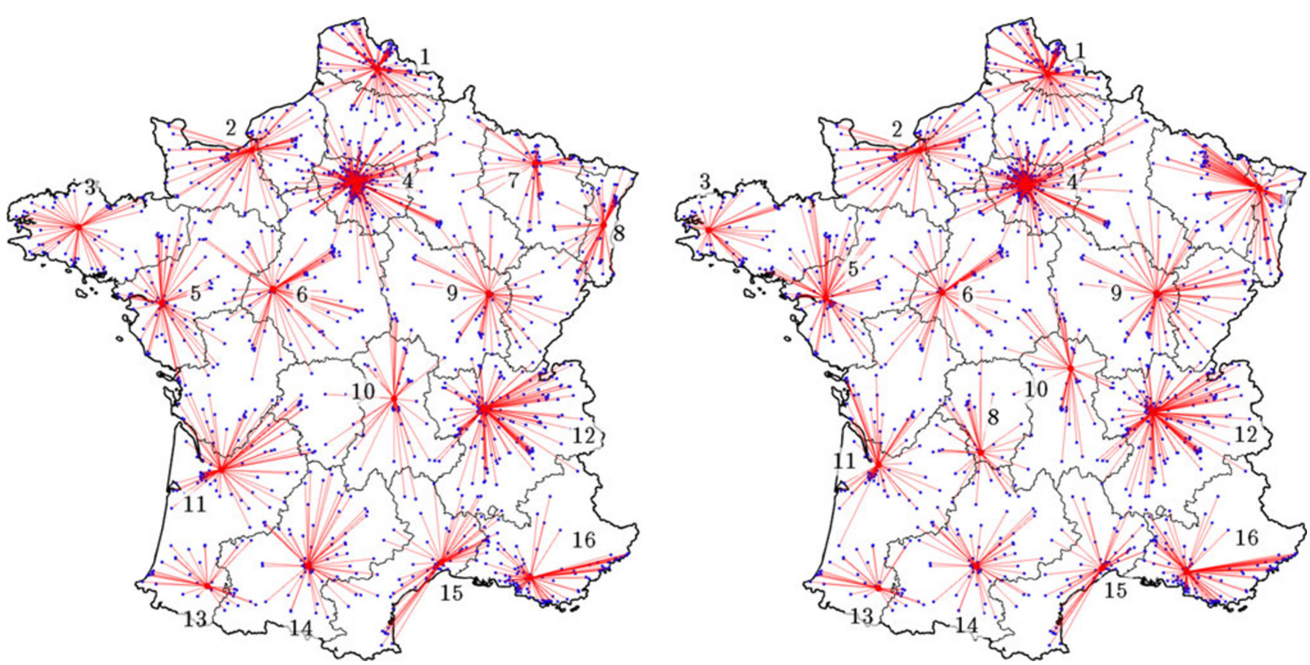

Fig. 10 Graphical comparison of location solutions (*left* S^{classic}, *right* S^{tour})—Example 3

Table 16 Percentage change of tour planning key figures of T^{tour} in comparison to T^{classic} for the examples (values less than 0 implies a reduction)

Example Test instance	1 TI 1	2 TI 2	3 TI 3
$costs(\Delta C \cdot (-1))$	−7.5	−12.7	−7.8
costs (incl. service costs)	−4.0	−8.0	−6.3
tours	−4.0	−7.1	−5.2
$\text{MAD}^{\text{tours}}$	90.7	26.9	−10.1
$\text{MAD}^{\text{customers}}$	55.6	33.2	10.4
$\text{MAD}^{\text{amount}}$	53.0	32.6	9.8
$\text{AVG}^{\text{stops}}$ and AVG^{cap}	4.2	7.7	5.5
$\text{MAD}^{\text{stops}}$	−17.1	−8.6	−11.2
MAD^{cap}	−14.5	−6.4	−13.1
AVG^{rel}	9.5	1.6	3.4

The implemented cost apportionment approach was tested with six test instances, out of which three were from practice. In most cases, the cost apportionment approach led to a cost reduction. By the cost apportionment approach, it was possible to achieve cost reductions of up to 22 % compared to the classical location planning approach. The maximum cost increase in the cost apportionment approach was never greater than 2.6 %. Cost reduction was in most cases accompanied by a reduction in the number of tours, an increase in the average number of stops on tours, and an increase in the average capacity utilization of vehicles. In addition, there was a reduction in the MAD of the number of stops on a tour and capacity utilization of vehicles. However, the MAD of the number of tours and customers as well as the handling amount of the depots increased.

The influence of certain parameters on cost reduction could be identified in the test instances. Therefore, the larger the cost reduction, the lower is the maximum tour duration, the lower the number of locations, and the more unequal the customer distribution in the distribution area.

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