Recent Advances in Strategic and Tactical Planning of Distribution Subnetworks for Letter Mail

Halil Ibrahim Gündüz, Christoph Klemens Hempsch and Hans-Jürgen Sebastian

Abstract This paper considers the postal logistics area, more precisely, the distribution networks for letter mail. A main service provided by postal companies is letter mail transportation and delivery. In this market segment there have been two key efforts during the last few years: reduction in transportation and delivery time (service quality) and minimization of costs under service quality constraints. Both efforts—reduction of service time and minimization of costs for providing the promised services—have a strong impact on the quality of the strategic and the tactical planning phases of the respective distribution networks. The Operations Research type of analytical models used in the strategic and tactical planning phases of distribution networks in postal organizations are: facility location, location routing, service networks design, and vehicle routing and scheduling models. In this article we introduce the structure of a typical distribution network for letter mail and for parcel mail, and we describe the main subnetworks. This paper is also concerned with projects on optimization of such subnetworks. Therefore, we have selected three projects dealing with different subsystems and covering the strategic and the tactical planning phases as well. The projects are in the areas of collecting mail from mailboxes (vehicle routing), replanning of delivery station locations (facility location combined with vehicle routing), and reducing deadheading in the last mile (facility location combined with vehicle routing). Each of the projects covers system analysis, modeling, development of optimization algorithms, and a software prototype.

H.I. Gündüz (✉) · H. Sebastian
Deutsche Post Chair of Optimization of Distribution Networks,
RWTH Aachen University, Kackertstr. 7, 52072 Aachen, Germany
e-mail: guenduez@dpor.rwth-aachen.de

H. Sebastian
e-mail: sebastian@dpor.rwth-aachen.de

C.K. Hempsch
Deutsche Post AG, Charles-de-Gaulle-Str. 20, 53113 Bonn, Germany
e-mail: hempsch@deutschepost.de

H.-J. Sebastian et al. (eds.), *Quantitative Approaches in Logistics and Supply Chain Management*, Lecture Notes in Logistics,
DOI 10.1007/978-3-319-12856-6_5

1 Introduction

The increasing market competition and the service focus of customers force logistics service providers, such as postal organizations and express shipment companies, to evaluate and to continuously improve their networks for letter, parcel, and freight mail.

The key service provided by postal companies is letter mail and parcel mail transportation and delivery. In this market segment there have been two key efforts during the last few years:

- reduction in transportation and delivery time (service quality)
- minimization of costs under service quality constraints

In addition, the goal of 'green logistics' has become more and more important and is today firmly established as one of the core values of several leading postal service providers, such as Deutsche Post DHL.

Both efforts—the reduction of service time and the minimization of costs for providing the promised services—have a strong impact on the quality of the strategic and the tactical planning phases of the respective distribution networks. Instead of using simple techniques in order to get a *quick solution*, advanced model-based optimization and simulation are needed today.

Optimization of facility locations and the allocation of *customers* to the facilities, such as terminals, depots, sorting centers, and hubs, are the most important decisions within the strategic planning phase. If the facilities and their locations are selected and the allocation of *customers* is done simultaneously, the tactical planning phase includes the optimization of transportation and delivery (*the last mile*) in order to determine the routes and the schedules for the fleet of vehicles used in the distribution network. The Operations Research type of analytical models used in the strategic and tactical phases of planning of distribution networks in postal organizations are: facility location, location routing, service network design, and vehicle routing and scheduling models (problems).

1.1 The Distribution Networks for Letter Mail and Parcel Mail

In this section we introduce the structure of a typical distribution network for letter mail, parcel mail, or both types of mail together (see also [17]). In Fig. 1 such a network is shown, and numbers for sorting centers and delivery stations are mentioned that relate to the distribution network of Deutsche Post DHL for letter mail within Germany. This network can be considered to be composed of four main *stages* (subnetworks):

- Stage 0—mail collection: This subnetwork collects the mail from different mail sources, and uses consolidation points in order to transport the mail to the sorting centers.

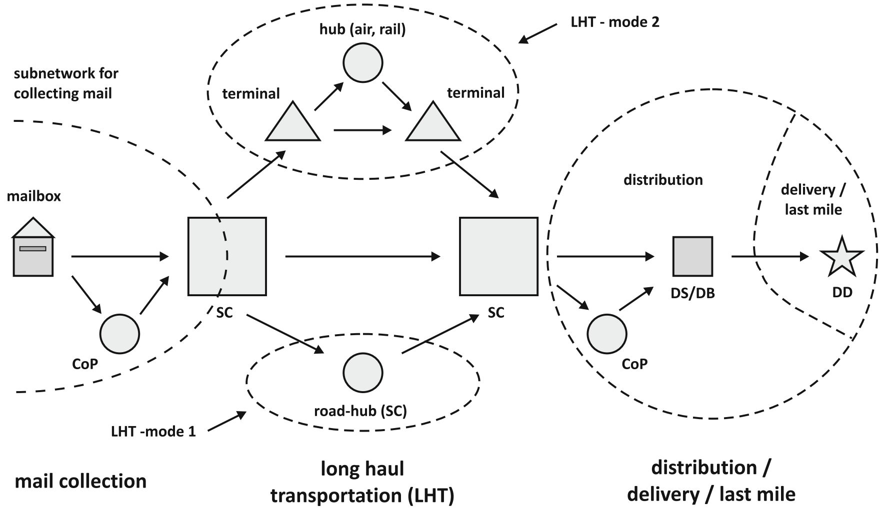


Fig. 1 Components/subnetworks of a distribution network for letter mail and parcel mail

- Stage 1—long haul transportation (LHT): This subnetwork realizes the exchange of mail between sorting centers. The idea is to use consolidation and bigger or faster vehicles for the long distances between sorting centers [5].
- Stage 2—distribution: These distribution networks (used in a more narrow sense) distribute the mail from sorting centers to mini-hubs (so-called delivery stations or delivery bases), where the final preparation for the postmen's tours takes place and where the postmen usually start their delivery routes (the last mile).
- Stage 3—delivery (last mile): Postmen visit their assigned delivery districts in order to deliver the mail to private households or to business customers.

If one were to compare such a distribution network in postal logistics with a classical distribution network for physical goods, several important differences would become evident (e.g. a small number of product types in the postal case, but a huge number of mail sources, mail final destinations, and commodity exchange processes within the same stage). We go slightly further into the details of the stages (subnetworks) described above in order to be able to characterize the special optimization projects that we will discuss in Sects. 2–4 in detail. First, we consider the subnetworks for collecting mail. Usually, each sorting center (SC) has its own network for mail collection. The main objects belonging to the mail collection networks are

- mail sources, e.g., mailboxes, business customers, retail stores (may also be used as consolidation terminals), and
- collection routes, which perform mail transportation from the mail sources to their allocated sorting centers.

Sorting centers for letter or parcel mail, respectively, are big automated facilities which implement the sorting part (the *production*) within these distribution networks.

Sorting centers for letter mail work in two different modes: SCA and SCE. The SCA mode performs the sorting of collected mail with respect to the destination SC (in Germany, the destination SC is characterized by the first two digits of the zip code). The SCE mode undertakes automated sorting of the incoming mail from the long-haul transportation network with respect to distribution (from the SC to the delivery stations) and with respect to the delivery (last mile) (sorting according to the sequence in which the postman visits his DD). Usually, the geographic areas allocated to the SCA mode and the SCE mode of an SC are identical. However, there is an option to use some of the sorting centers during several time periods of the year as SCE centers only. Physically, the SCA and SCE sorting centers are the same. An SC can operate either in SCA or in SCE mode, depending on time of day. This is possible because of the high degree of flexibility of the automatized sorting machines.

Long haul transportation means the global area transportation network which connects the sorting centers with each other. Consolidation is used in order to transport big quantities of mail over longer distances using larger vehicles or using multi-modal transportation (e.g. road-air, road-rail).

Finally, there are subnetworks for distributing the mail from an SC (working in SCE mode) to the *delivery stations* and the so-called *last mile*. A delivery station (DS) is a mini-hub, where the final preparation for delivery takes place as performed by the postmen. Then, the postmen pick up their sorted mail and start the delivery process, each of them visiting their assigned delivery district (DD) by car, by bicycle, or on foot in a predefined (ideally optimized) sequence.

Figure 1 shows a more schematic picture of a distribution network for letter mail and parcel mail. The subnetworks and their components are denoted by the abbreviations introduced before. In order to illustrate the dimension of an instance of such a distribution network, we give some characteristic approximate numbers of Deutsche Post DHL distribution network for letter mail within Germany:

- 40 million final destinations, including 3 million business customers
- approximately 68 million letters (of different types) every working day
- 1,08,000 mailboxes
- 82 sorting centers plus the international postal center in Frankfurt
- 3,100 delivery stations and 14,000 offices (retail)
- 53,000 delivery districts (3,500 visited on foot, 18,500 by bicycle, and 31,000 by car)

There are approximately 80,000 postmen employed by Deutsche Post DHL within the last mile in Germany.

1.2 Strategic and Tactical Planning of Subnetworks

The huge size of the networks considered above does not allow the development of an overall optimization model which has a chance of being solved either exactly or approximately. Also, the acquisition of all data needed as an input for such a model seems to be either impossible or much too demanding in terms of time and costs. Therefore, in order to reduce complexity, the well known planning phases are introduced. In addition, the overall network is heuristically decomposed into subnetworks by introducing an overall service-quality level for the whole network (e.g., next-day delivery for all postal products) and by assigning time windows and cut-off-times to the predefined subnetworks (see Fig. 1), such that the overall service quality can be fulfilled. This approach is described in more detail in [16]. For example, the long-haul transportation network for letter mail in Germany has a time window on weekdays from 9 p.m. to 4 a.m. The cut-off time for the mail collection network is 9 p.m. Comparable standards are found in [14] for transportation analysis and cost-savings opportunities in the surface-transportation network at the United States Postal Service. In the past, the Deutsche Post Chair of Optimization of Distribution Networks at RWTH Aachen University and its predecessors have successfully executed a number of projects dealing with the optimization of subnetworks of the distribution network in postal logistics, e.g.,

- the optimization of the Deutsche Post Night-Airmail network for letter mail (LHT subnetwork for letter mail) [3, 4, 8]
- the delivery station location optimization
- the swap body container transportation optimization problem (LHT network for parcel mail) [16]
- the reassignment of mail sources to sorting centers

This paper is also concerned with projects on the optimization of such subnetworks. We will describe the approaches and the results of three recent projects in more detail. We have selected these projects from different subsystems of the overall network, and we cover both the strategic and the tactical phases. The projects are in the areas of

- collection of mail from mailboxes (vehicle routing)
- replanning of delivery station locations (facility location combined with vehicle routing)
- reduction of deadheading in the last mile (sequential facility location and vehicle routing approach)

Each of the projects covers system analysis, modeling, development of optimization algorithms, and implementation of a software prototype (decision support system).

2 Optimization of Mailbox Collection Tours

In the collection part of a postal logistics network, mail is collected from different types of locations, e.g., mailboxes, business customers, and retail stores. The different types of pick-up points can be distinguished by characteristics, such as their service time windows, the collection frequency, or collected mail volume. In this section we focus on the collection of letter mail from mailboxes. Even though mail volume is generally small at mailboxes, mail often needs to be collected multiple times a day, as mailboxes may fill up quickly. This especially holds if they are located in busy spots, e.g., train stations. In Germany the collection times are noted on each mailbox individually, and mail may not be collected from a mailbox before this specific time. For this reason, service time windows in collection tours are determined by the earliest arrival time, which is the collection time displayed on a mailbox. The latest arrival time at a mailbox is not restricted as long as mail is not *overflowing* out of the mailbox.

Multiple studies concerning the optimization of mailbox collection tours have been published, e.g., by Laporte et al. [11] for Canada Post Corporation in Montreal, by Mechti et al. [12] for the French postal service, and by Tarantilis et al. [19] for some known benchmarks from the literature. None of them consider restricted vehicle capacities, as mail volume on a tour is small in general. However, the latest arrival time at a depot or the maximal duration of tours prevent the introduced models from visiting all mailboxes with a single tour.

2.1 Modeling and Solving

The optimization of mailbox collection tours may be modeled as a vehicle routing problem (VRP) [20, 21]. As mentioned above, for the optimization of mailbox collection tours at Deutsche Post DHL, time windows need to be considered. Also, as we are taking multiple sorting centers into consideration, we may change the allocation of mailboxes. This decision is implicitly made by assigning a mailbox to a tour, as each tour has a predefined start depot and end depot. Unlike other known models, in our application, sorting capacities at mail sorting centers are restricted. Yet, as collection tours may arrive until a defined final sorting time (cut-off time) has been reached, the restricted capacity cannot be modeled as a single resource. Much more, a certain arrival rate of mail at the sorting center must be met in order to guarantee completion of sorting before cut-off. For model complexity reasons, this arrival rate may be discretized into a set of points in time within the sorting time window of a depot. Then, the mail volume arriving at the depot with a tour later than a certain time is restricted. Figure 2 shows an example of discretization of sorting capacities for a generic sorting center, where $B^g(\tau)$ denotes the letter mail quantity that can be processed at depot g later than time τ.

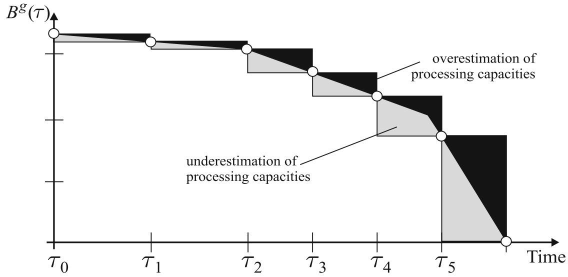


Fig. 2 Example of a discretization of a time-varying processing capacity function

The problem was modeled as a multi-depot vehicle routing problem, where the sorting capacities of the depots (sorting centers), which may vary over time, are taken into account as restricted inter-tour resources [6], i.e., resources that are restricted not to one tour but for all tours at the same time. The mathematical model and its parameters, decision variables, restrictions, and the objective function are described now.

Sets:

C	set of customer nodes
G	set of depot nodes
K	set of vehicles or tours
V^k	set of feasible nodes for tour $k \in K$
A^k	set of feasible arcs for tour $k \in K$
L	set of points in time

Parameters:

$o(k)$	start node/origin of tour k
$d(k)$	end node/destination of tour k
a_i	lower bound for a resource at node i
b_i	upper bound for a resource at node i
t_{ij}^k	resource demand on direct link from node i to j for tour $k \in K$
$B^g(\tau_\ell)$	mail that can be processed at depot g later than time ℓ
n_g	number of tours that end at depot g
$k(g, h)$	the hth vehicle ending at depot g

The objective (1) of the model minimizes the total costs accumulated along all tours. Constraints (2) ensure that each customer $i \in C$ is visited by one and only one tour. Each tour $k \in K$ contains a unique start depot $o(k)$ and also a unique end depot $d(k)$ (see constraints (3)). The flow conservation of a tour $k \in K$ at node $i \in V^k$ is represented by constraints (4). With the binary routing variables x_{ij}^k (5), constraints

Decision variables and resource vectors:

$x_{i,j}^k$	binary variable indicating that arc (i, j) is visited by tour k
$T_{d(k)}^{k,cost}$	accumulated costs of tour k at its destination depot $d(k)$
$T_i^{k,load}$	accumulated mail pick-up volume at node i of tour k

$T_i^{k,time}$ accumulated travel and waiting time at node i of tour k
$S^g_{\ell,h}$ partial sum of all loads arriving at depot g later than time ℓ for the first $1, 2, \ldots, h$ tours
$f_{ij}(T_i^k)$ $\max\{a_i, T_i^k + t_{ij}^k\}$

(6) and (7) simply state that the paths $P = P(x^k)$ on each tour $k \in K$ have to form resource-feasible paths. Inequalities (8) guarantee that the sequence of partial sums is non-decreasing. Constraints (9) model the interdependency between arrival time and collected load of a tour, and the corresponding partial sum. If tour k with depot destination d_k arrives after τ_ℓ ($T_{d(k)}^{k,time} > \tau_\ell$), then the hth partial sum $S^g_{\ell,h}$ must exceed $S^g_{\ell,h-1}$ by the delivered volume $T_{d(k)}^{k,load}$ at depot d_k. If τ_ℓ ($T_{d(k)}^{k,time} \le \tau_\ell$) holds, then constraints (8) and (9) allows the setting of $S^g_{\ell,h} = S^g_{\ell,h-1}$. Through constraints (10), processing capacities after time ℓ are restricted. Note that constraints (8)–(10) are non-linear.

$$\min \quad \sum_{k \in K} T_{d(k)}^{k,cost} \tag{1}$$

$$\text{s.t.} \sum_{k \in K} \sum_{j:(i,j) \in A^k} x_{ij}^k = 1 \quad \forall i \in C \tag{2}$$

$$\sum_{j:(o(k),j) \in A^k} x_{o(k),j}^k = \sum_{i:(i,d(k)) \in A^k} x_{i,d(k)}^k = 1 \quad \forall k \in K \tag{3}$$

$$\sum_{j:(i,j) \in A^k} x_{ij}^k - \sum_{j:(j,i) \in A^k} x_{ji}^k = 0 \quad \forall k \in K, i \in V^k \tag{4}$$

$$x_{ij}^k \in \{0, 1\} \quad \forall k \in K, (i, j) \in A^k \tag{5}$$

$$T_i^k \in [a_i, b_i] \quad \forall k \in K, i \in V^k \tag{6}$$

$$x_{ij}^k (f_{ij}(T_i^k) - T_j^k) \le 0 \quad \forall k \in K, (i, j) \in A^k. \tag{7}$$

$$S^g_{\ell,h-1} \le S^g_{\ell,h} \quad \forall g \in G, \ell \in L, h \in \{2, \ldots, n_g\} \tag{8}$$

$$(T_{d(k)}^{k,time} - \tau_\ell)(S^g_{\ell,h-1} + T_{d(k)}^{k,load} - S^g_{\ell,h}) \le 0 \quad \forall g \in G, \ell \in L, h \in \{2, \ldots, n_g\}, \quad k = k(g,h) \tag{9}$$

$$0 \le S^g_{\ell,h} \le B^g(\tau_\ell) \quad \forall g \in G, \ell \in L, h \in \{2, \ldots, n_g\} \tag{10}$$

The model and its solution are based on the unified modeling and solution framework by Irnich [10]. Tours are connected to a giant tour, where resources, such as time and load, are restricted at each node. The consumption of resources along arcs or tour segments is calculated through so-called resource extension functions (REFs) (see [9]). To find a good feasible solution quickly for a problem instance, customer nodes are iteratively inserted into dummy tours and re-inserted into tours through a variable neighborhood descent (VND) algorithm. Also, iterations of destroy moves followed by the VND are used to diversify solutions and to explore a bigger part of the solution space. Details of the solution approach are described in [6, 10].

Fig. 3 Comparison of total tour length (in minutes) of today's tours and an optimized tour plan for two neighboring pilot regions (denoted as areas A and B)

2.2 Implementation

At Deutsche Post DHL, most mailbox collection tours start and end at a depot. Here, they pick up the keys for the mailboxes as well as a scanner, which they need to document the mailboxes visited along a collection tour. After visiting all mailboxes, the tour returns to the SC, bringing in the collected mail, the keys, and the scanner.

For the optimization of the collection tours, first the current tour plan is analyzed. The arrival rate of mail volume with the current tours arriving at an SC is set as the sorting center's capacity. Mail brought in by new tours must not exceed this arrival rate, i.e., with an optimized tour plan, more volume should arrive earlier than today at each SC.

For analysis purposes, we used real data of two neighboring regions representing urban and rural areas. Figure 3 shows the total time of today's tour plan and the result of our optimization for the pilot regions. The tours contain more than 2,000 stops, as each mailbox may be emptied multiple times per day. Through our optimization, more than 20 % of total tour time is saved in *Area A* (mostly urban areas) and about 10 % in *Area B* (mostly rural areas). The results show that this approach is suitable for urban areas as well as for rural areas. We assumed that, a simultaneous optimization of neighboring areas could better exploit the optimization potentials. When solving a multi-depot VRP with time windows (MDVRPTW) with two depots instead of two separate single depot vehicle routing problems with time windows, 13 % of total tour time may be saved in *Areas A + B*. Despite the promising result, the absolute decrease of total time is less than the sum for *Area A* and *Area B*. The reason for this result is the heuristic approach, the large number of stops for *Areas A + B* and therefore the growing complexity. The influence of time-varying sorting capacities on the total tour length is shown in Fig. 4. Even though the optimized tour plan (*MDVRPTW with capacity constraints*) is about 5 % better than today's tour plan (*Today*), tour length can be significantly shortened when relaxing or removing the

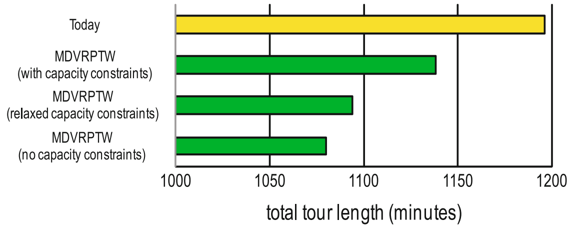


Fig. 4 Influence of time-varying sorting capacity constraints on total tour length

capacity constraints. This shows that every effort needs to be made to model sorting capacities as accurately as possible.

Thanks to the results of successful pilots with the implemented prototype, the model introduced above is today part of the software used for the operational planning of mailbox collection tours at Deutsche Post DHL. Since September 2008, Deutsche Post DHL has realized a significant cost reduction by optimizing the mailbox collection tours using this software.

3 Optimization of Delivery Stations

We consider now the subnetwork *distribution and delivery of the last mile*. Our goal is the optimization of the delivery processes within this subnetwork by strategic network design decisions. We introduced this network briefly in Sect. 1.1. The relevant objects are sorting centers and the delivery stations for letter mail. Delivery stations are mini-hubs where the final preparation (final sorting) of mail for the delivery takes place (performed by the postman) and where the postman starts the delivery tours covering his DD. Figure 5 shows a simplified schematic picture of the subnetwork *distribution and delivery of the last mile*.

In order to better understand the transportation link in stage 2 of the network, we consider Fig. 6. In reality, the postman moves from the DS to the first customer of

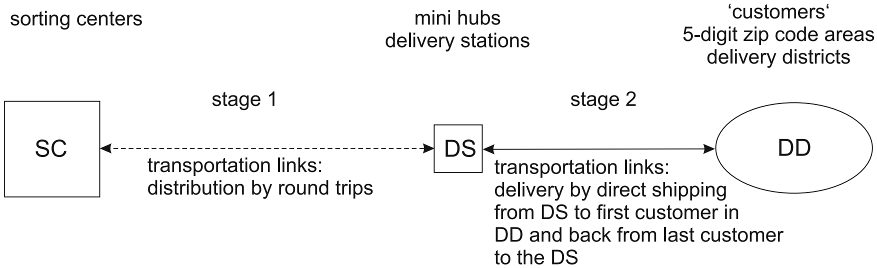


Fig. 5 Schematic view of the subnetwork *distribution and delivery of the last mile*

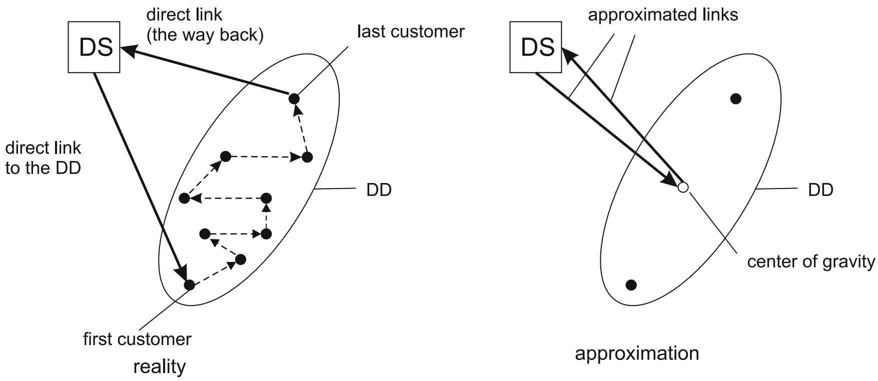


Fig. 6 Raw approximation of a delivery district by its center of gravity

the DD and after visiting all customers of the DD, the postman returns from the last customer to the DS. Of course, the DS to first customer, last customer to DS links are not productive from the standpoint of the core delivery process. They take time and therefore the length of these unproductive links should be minimized. In order to simplify the model, we concentrate the postman tours within the delivery districts by using the center of gravity of the DD instead of considering a first and a last customer of the postman tour. Then, we get an approximated distance: *DS to center of gravity of DD*. The transportation links in stage 1 (see Fig. 5) are much more complicated, because distribution from the SC to the assigned set of delivery stations is organized by round trips. We will consider the type of round trips used in stage 1 later in detail. After describing the network structure and the transportation processes, we have to define the optimization problem. Of course, one may think about different, more -or less- complex and complicated problems. We focus here on the following scenario:

- The sorting centers for letter mail belonging to a well defined geographic area are given (i.e. locations and capacities are given). The well defined geographic area is the area allocated to the considered SC (see Sect. 1.1).
- The allocated area considered above is composed of a set of 5-digit zip code areas and is, at the same time, cut into a set of delivery districts. These delivery districts and the routes used by the postman to visit them are assumed to be given.
- There is a set of potential DS locations consisting of existing delivery stations and new locations. Each location belonging to the set of potential DS locations is called a *candidate location*.

The problem is to select DS locations from the set of candidate locations such that service quality requirements (restrictions) are fulfilled and an overall cost function becomes minimal. We will call this problem in the following *selection of optimal DS locations*.

3.1 Mathematical Formulation and Solution Approach

The solution approach to the problem *selection of optimal DS locations* is model-based. The mathematical model and its parameters, decision variables, restrictions, and the objective function will be described now.

Notations:

J set of zip-code areas j
SI set of indices of potential delivery locations DL
SH set of indices of sorting centers SC
SS set of indices of other relevant locations SO
$SI = \{1, \ldots, n_I\}$ n_I number of potential delivery locations
$SH = \{n_I + 1, \ldots, n_I + n_H\}$ n_H number of SCs
$SS = \{n_I + n_H + 1, \ldots, n_I + n_H + n_S\}$ n_S number of SOs

A potential delivery location i, where $i \in I$, is either a DS (letter mail network LN) or a delivery base (DB) (parcel mail network PN). Therefore, we get: $SI = SI^{\text{LN}} \cup SI^{\text{PN}}$ and $SI^{\text{SYN}} = SI^{\text{LN}} \cap SI^{\text{PN}}$. SI^{LN} and SI^{PN} denote the index sets of the potential delivery locations for the letter mail or the parcel mail network. SI^{SYN} contains those potential delivery locations which can be used for both networks. Thus, the model takes into account the synergies of both the letter mail and the parcel mail networks.

Parameters:

f_i fixed costs for opening delivery location i
f_i^o annual fixed costs for operating delivery location i
$\widetilde{y}_i$ 1 if DL i is open in the initial situation, otherwise 0

We distinguish between opening and annual operating fixed costs. Both costs occur if a potential DL is selected and does not exist in the current configuration. Otherwise only the annual operating fixed costs occur.

Decision variables:

$x_{ij} \in \{0, 1\}$ for $i \in SI$ and $j \in J$
$y_j \in \{0, 1\}$ for $i \in SI$

$x_{ij} = 1$ holds if zip-code area j is assigned to the potential DL i, $x_{ij} = 0$ otherwise. $y_i = 1$ holds if the potential delivery location i is selected ('open'), $y_i = 0$ otherwise.

Restrictions:

$$\sum_{i \in SI} x_{ij} = 1 \ \forall \ j \in J \tag{11}$$

Each customer's demand (zip-code area $j \in J$) is completely fulfilled by delivery locations SI. Together with $x_{ij} \in \{0, 1\}$, Eq. (11) means *single sourcing*. Each zip-code area is completely assigned to exactly one DL.

$$\sum_{i \in SI^{\mathrm{LN}}} x_{ij} = 0 \; \forall \; j \in J^{\mathrm{PN}} \tag{12}$$

$$\sum_{i \in SI^{\mathrm{PN}}} x_{ij} = 0 \; \forall \; j \in J^{\mathrm{LN}} \tag{13}$$

The set J of zip-code areas contains, for example 5-digit zip-code areas j. A zip-code area of this kind is covered by delivery districts for letter or for parcel mail separately and also by districts which are designed for combined letter and parcel mail delivery. J^{PN} denotes the set of delivery districts for parcel mail delivery only and J^{LN} the set for letter mail delivery only. Then, (12) means that a delivery district for parcel mail only cannot be allocated to a delivery location for letter mail only and vice versa (13). In addition, we have a capacitated problem:

$$\delta_{ij} x_{ij} \leq d_i^{max} \; \forall \; i \in \; SI \text{ and } j \in J \tag{14}$$

This means that the demand δ_{ij} of zip-code area j for a sorting area within the DL $i \in SI$ must be smaller than the capacity d_i^{max} of the DL. If the potential DL i is not open, $y_i = 0$, then it is not allowed to assign zip-code areas to this not-selected delivery facility.

$$x_{ij} \leq y_i \; \forall \; i \in SI \text{ and } j \in J \tag{15}$$

Objective function:

$$\min z = \sum_{i \in SI} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in SI} \left(f_i (1 - \widetilde{y}_i) y_i + f_i^o y_i \right), \tag{16}$$

whereby c_{ij} represents allocation costs if the zip-code area j is assigned to the DL $i \in SI$ (costs for the links from delivery location i to the center of gravity of a DD belonging to j, aggregated over all delivery districts belonging to j).

The term $\left(f_i (1 - \widetilde{y}_i) y_i + f_i^o y_i \right)$ describes annual fixed costs related to DL i and the fixed costs for opening the location i. In the case where delivery location i already exists ($\widetilde{y}_i = 1$), only annual operating fixed costs f_i^o apply.

The mathematical model can be characterized as a two-stage facility location problem. Also, it considers the synergies of both the letter and the parcel mail networks, which makes it interesting on the one hand but also very complex on the other. Problem instances become too big for computing exact solutions using the existing solvers and hardware. The approach is adapted to a replanning problem in contrast to a complete new network design task. This means that some of the existing DS/DB locations will remain stable while others are questionable. Also, there are existing round trips with related costs in the first distribution stage. These round trips should be taken into account either by the model or by the solution approach, which extends the problem in the direction of a location routing problem [13].

Concluding, we decided to develop a (meta-)heuristic approach, which was designed and implemented by Hermanns [7]. Next, we explain this iterative 3-phase heuristic approach.

- Start with the existing solution (distribution/delivery network). The algorithm starts with the existing delivery locations and routes, checks feasibility, and computes the related costs.
- Each iteration consists of 3 phases in the sequence:

1. location phase
2. allocation phase
3. routing phase

Location Phase

Selection of locations (from the set of potential delivery locations) which appear *attractive*, to be used as DS/DB-facilities. This selection is independent of allocation or routing decisions.

Allocation Phase

The locations chosen in phase 1 are now given. Customers (meaning delivery districts) are allocated to these locations. If there is no feasible allocation (e.g. because the capacities of the facilities selected in phase 1 are too small in order to satisfy the customer demand) the solution determined in phase 1 cannot be accepted. If a termination criterion is not fulfilled after diversification/intensivation steps, phase 1 must be repeated. In order to check the feasibility of the decisions made in phases 1 and 2 and to compute the related cost, the mathematical model described above is used.

Routing Phase

From the existing solution we know an existing configuration of locations (and related facilities), an allocation, and an existing set of routes (start = iteration 0). The same applies after each iteration i. After phases 1 and 2 of iteration i+1, we know the changes in locations and allocations compared to iteration i. Therefore, the routes belonging to iteration i have now to be modified such that the location and allocation decisions of iteration i+1 are taken into account.

After phases 1 to 3, a feasible solution has been constructed. If this solution is better than the best known solution up to iteration i+1, it becomes the new best known solution. Otherwise, the algorithm either stops or continues with a diversification step.

In the following we present a modified approach, which can be characterized thus:

- The location phase (phase 1) controls the algorithm. We use different operators e.g. the ‘add’ and ‘drop’ operators, which characterize the neighborhoods for local search. Also, we introduce a diversification strategy in phase 1.

- After selecting an operation in phase 1 (e.g. adding a closed candidate DL), we solve the resulting allocation problem in phase 2. This can be done by using a model-based approach applying a commercial MIP solver or by specialized algorithms [7].
- Now, within this add/drop-loop (phase 1) we know the related optimal allocation decisions and are therefore able to move to phase 3 in order to determine the best related routing decisions. This is done by operations which modify the existing routes by a route in the neighborhood.

Figure 10 shows the flow of the used heuristic. In the prototype tool for planning DS locations (TOPAS), the allocation problem in phase 2 is solved by a simple heuristic (nearest location) in the uncapacitated case and by a knapsack algorithm in the capacitated case. The overall algorithm is implemented as a tabu search and as a simulated annealing metaheuristic as well [7]. The most interesting component of the algorithm is the modification of the existing routes (known from the previous iteration) taking into account the new location/allocation decisions. We will illustrate the TOPAS approach to this problem using an example. First, we show the complexity of routes in this application area.

Example illustration

Let us assume that a route t^0 contains several locations. We denote by

- $H = \{SC1\}$ the set of sorting centers,
- $I = \{DS1, DS2, DS3, DS4\}$ the set of potential delivery stations, and
- $S = \{SO1, SO2\}$ set of other relevant (for the first distribution stage) locations.

In Fig. 7 the initial route $t^0 = (SC1, SO1, DS1, DS2, SO2, DS3)$ is illustrated. Now, we consider an add move in phase 1, which adds $DS4$. In phase 2, customer 2 becomes allocated to $DS4$. Then, Fig. 8 shows a new tour t^1, which is generated by inserting $DS4$ between $DS1$ and $DS2$ and by deleting the direct link from $DS1$ to $DS2$.

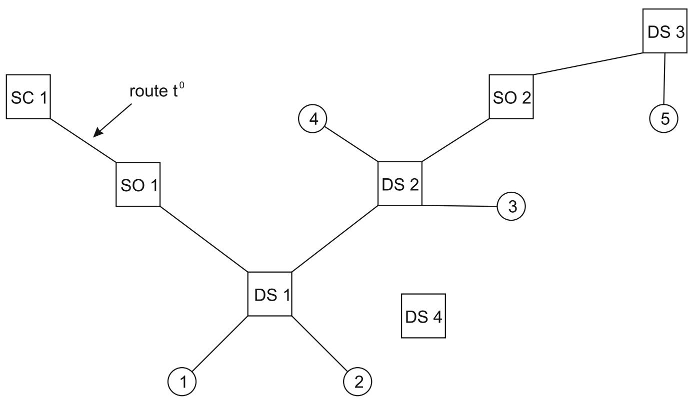


Fig. 7 An initial route t^0

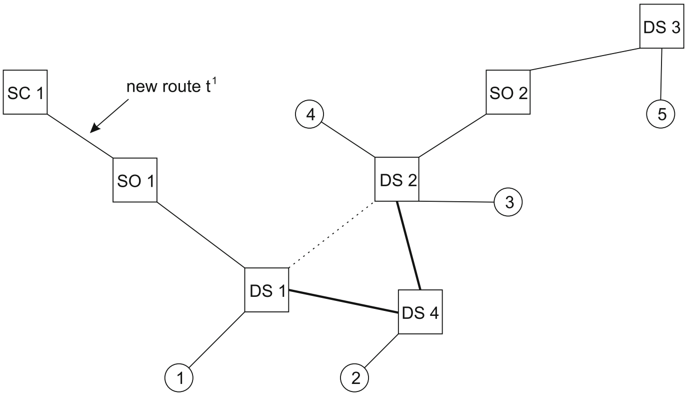


Fig. 8 New route $t^1 = (SC1, SO1, DS1, DS4, DS2, SO2, DS3)$ after an add move in phase 1, re-allocation in phase 2, and an insertion step in phase 3

Finally, in order to illustrate that different operations in phase 1 and different types of routes require different algorithmic solutions, we consider a second example, where the operator in phase 1 is the drop move and the considered tours are so-called central tours from the sorting center $SC1$ to delivery locations $DS1$, $DS2$, and $DS3$. The delivery stations have customers j_1, j_2, and j_3 allocated to them, which represent zip-code areas or regions composed of zip code areas. After dropping $DS1$, the tour $t2^0$ becomes shorter $t2^1$. In iteration 2, because of the additional dropping of $DS2$, all three customers j_1, j_2, and j_3 must be allocated to $DS3$. The tours $t1^2$ and $t2^2$ are now identical (see Fig. 9). All algorithms for the different categories are described in detail in [7].

The software prototype TOPAS was first applied for the optimization of the delivery stations in the year 2008. Since 2009, Deutsche Post DHL has achieved extensive economies by replanning the delivery station locations through using the prototype tool TOPAS. The implementation of TOPAS at Deutsche Post DHL, algorithms, numerical test and results, and economic results are described in [7] on pp. 139–160.

4 Reducing Deadheading on Postman Tours

In this section we consider now a part of the last mile of the letter mail network in Germany. Postmen start their workday at a DS with administrative tasks and the sorting of all/some letters according to the route they take when actually delivering mail. Since the DS is not necessarily located inside a postman's district, the postman tour may start with deadheading (from the DS to the first delivery point, see Fig. 11). It typically also ends with deadheading (from the last delivery point to the DS). In order to increase productivity, a reduction of these unproductive parts of the tour is reasonable. One way would be to set up many delivery stations close to or within each DD, but this would lead to increasing distribution costs (of stage 2, see Sect. 1.1) and

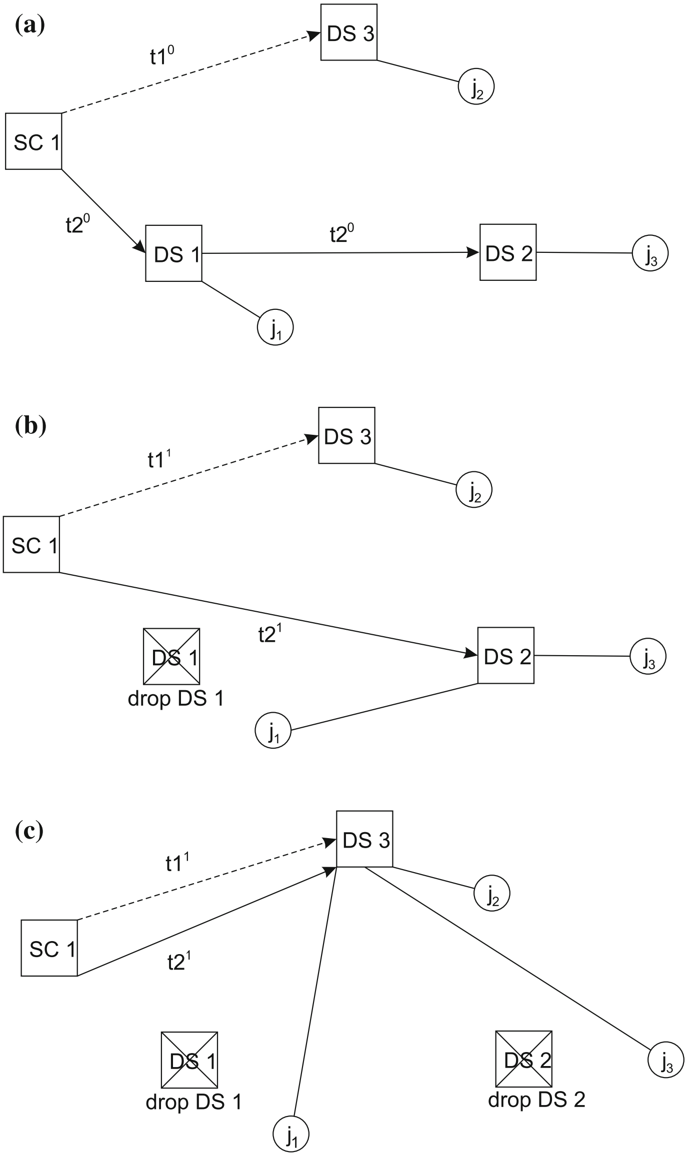
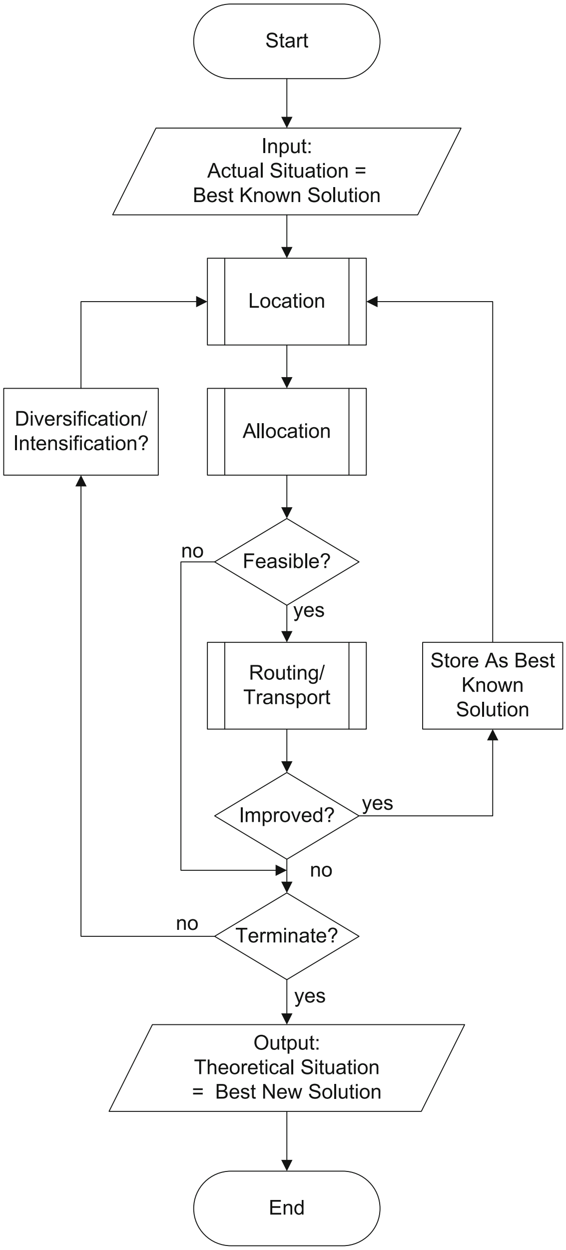


Fig. 9 Drop operations to different routes. **a** Two initial routes $t1^0$ and $t2^0$. **b** First iteration, one possible result after drop DS 1. **c** Second iteration, one possible result after drop DS 2

overhead/operating costs. Therefore, we are addressing the issue of how unproductive parts of postman tours can be reduced without introducing more delivery stations.

The solution to this problem is in the reorganization of the processes: The sorting and delivery of mail should be done by different employees. In this way, the

Fig. 10 Flow chart of TOPAS solution approach



preparation and some kind of sorting can be performed in the DS by specialized employees. Then, sorted mail is packed into boxes and shipped to transfer points by car. There, postmen take over the boxes and start the delivery within the delivery districts. An advantage of this solution is that transfer points have low operating

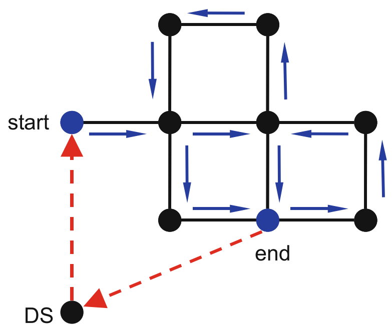


Fig. 11 Deadheading on a postman tour

costs and can be placed close to the delivery districts. Thus, postmen do not start their tours with deadheading, or at least they start with less deadheading. Finally, the task is to find the optimal number and location of transfer points, such that the sum of deadheading, transportation, and operational costs for transfer points is minimized (and the overall costs are lower than the costs for deadheading from the DS).

4.1 Mathematical Formulation

In order to model the problem, we assume that the set I of delivery districts and the set J of potential transfer points are known. Furthermore, operational costs (fix and variable costs) for transfer points, deadheading costs between each transfer point (TP) and DD, and shipment costs are known. Our approach for modeling and solving this problem is based on location routing theory [15] but it proceeds in two sequential steps: the first step is the determination of the number and location of transfer points, and the second step is the optimization of mail transportation costs from the DS to the transfer points.

The objective of the first step is to minimize the sum of deadheading and operational costs, whereby the following restrictions must hold: Each DD must be uniquely assigned to a TP. Further, because of employment laws, at least two postmen must start at the same TP. Additionally, due to space shortage at transfer points (these are, e.g., garages, car ports) a maximum number of postmen can work at the same TP. This problem is a capacitated warehouse location problem with single-sourcing constraints derived from [1]. Delivery districts relate to customers with demand 1 and transfer points to warehouses, where the capacity is defined by the maximum number of postmen at a TP. The mathematical formulation and its parameters, decision variables, restrictions, and the objective function will be described now.

Notations:

- I set of delivery districts
- J set of potential transfer points

The set of delivery districts is known in advance and the division of the delivery area is not a part of this problem. Further, the discrete set of potential transfer points is a subset of nodes within the street network of the delivery area.

Parameters:

f_j fixed costs of TP j
v_j variable costs of TP j
c_{ij} costs for deadheading between TP j and DD i
a_j minimum number of delivery districts assigned to an open TP j
b_j maximum number of delivery districts assigned to an open TP j

Fixed costs represent rent or leasing costs of a TP. Variable costs represent expenses per postman at a TP. Costs for deadheading are calculated as the minimum of the shortest paths from the TP j to each node of the DD i within the street network of the delivery area. The minimum of the shortest paths is multiplied by two (includes the way to and from the DD) and (time) travel costs. As mentioned above, the parameters a_j and b_j restrict the number of assigned delivery districts (postmen) to a TP j.

Decision variables:

$y_j \in \{0, 1\}$ binary variable indicating whether TP j is open or closed
$x_{ij} \in \{0, 1\}$ binary variable indicating whether DD i is assigned to TP j

$x_{ij} = 1$ holds if DD i is assigned to the potential TP j, $x_{ij} = 0$ otherwise. $y_j = 1$ holds if the potential TP j is selected ('open'), $y_j = 0$ otherwise.

$$\min \sum_{j \in J} f_j y_j + \sum_{j \in J} \sum_{i \in I} v_j x_{ij} + \sum_{j \in J} \sum_{i \in I} c_{ij} x_{ij} \tag{17}$$

$$\text{s.t.} \sum_{j \in J} x_{ij} = 1 \quad \forall \quad i \in I \tag{18}$$

$$x_{ij} \le y_j \quad \forall \quad i \in I, j \in J \tag{19}$$

$$a_j y_j \le \sum_{i \in I} x_{ij} \quad \forall \quad j \in J \tag{20}$$

$$\sum_{i \in I} x_{ij} \le b_j y_j \quad \forall \quad j \in J \tag{21}$$

$$x_{ij} \in \{0, 1\} \quad \forall \quad i \in I, j \in J \tag{22}$$

$$y_j \in \{0, 1\} \quad \forall \quad j \in J. \tag{23}$$

The objective function (17) is minimizing the sum of fixed, variable, and deadheading costs. Constraints (18) represent the single-sourcing constraints, which means that each DD must be assigned to exactly one TP. On the other hand, constraints (19) restrict the assignment of a DD to a TP if and only if the TP is selected.

A minimum number of delivery districts must be assigned to a selected TP (20), and the number of assigned delivery districts cannot exceed a given upper bound (21). Constraints (22) and (23) represent the binary requirement of the decision variables. This problem was solved with the commercial solver MOPS [18].

Once the number and location of transfer points are determined, the task of the second step is to ship the sorted mail to the transfer points. Service quality aspects force postmen to start their delivery at the first delivery point at approximately 8.00 a.m. and the sorting of mail to be finished by 6.30 a.m. in the DS. So the transportation of sorted mail to transfer points can be performed only during the time window from 6.30 to 8.00 a.m. This problem relates to a vehicle routing problem with time windows (VRPTW) (see [2]) and its solution approach is based on the unified modeling and solution framework by Irnich [10].

4.2 Implementation

For application scope, both described problems and used solving methods were implemented in a prototype. For a given set of delivery districts and potential transfer points, the optimal number and location of transfer points and route plans from the DS to the transfer points can be optimized. Further, for a period of time (from Monday to Saturday) the overall cost (sum of deadheading, operational, and shipment costs) can be compared to the cost of deadheading from the DS of the former situation. Figure 12 shows an example scenario for reducing deadheading with the prototype. The prototype window is composed of four areas and will be described in the following. For simplicity, we call the situation before installing transfer points *current state* and the situation after installing transfer points *new state*.

The first area (Fig. 12a) contains information about each DD. In the order of the columns we have the identifier, the mode of transport (by bicycle or on foot) in the current state, the mode of transport in the new state, the deadheading in meters of the current state, the deadheading in meters of the new state, the deadheading in minutes of the current state, and finally the deadheading in minutes of the new state. The last two rows contain the sum and average of deadheading in meters and minutes of both states.

We retrieve the optimization data from the second area (Fig. 12b). In the first column we have the identifier of the selected transfer points. The following columns contain for each chosen TP its fixed costs, variable costs, minimum and maximum number of possible assignments, and the number of assigned delivery districts and their identifiers.

From the third area of the prototype (Fig. 12c) we gain cost information on the current and new states for each scenario calculation. In the order of the columns we have the identifier, the number of chosen transfer points, the sum of operating costs per week, the sum of deadheading costs per week, the number of needed tours for mail shipment to the transfer points, shipment costs per week, overall costs per week of the new state, and finally overall deadheading costs of the current state.

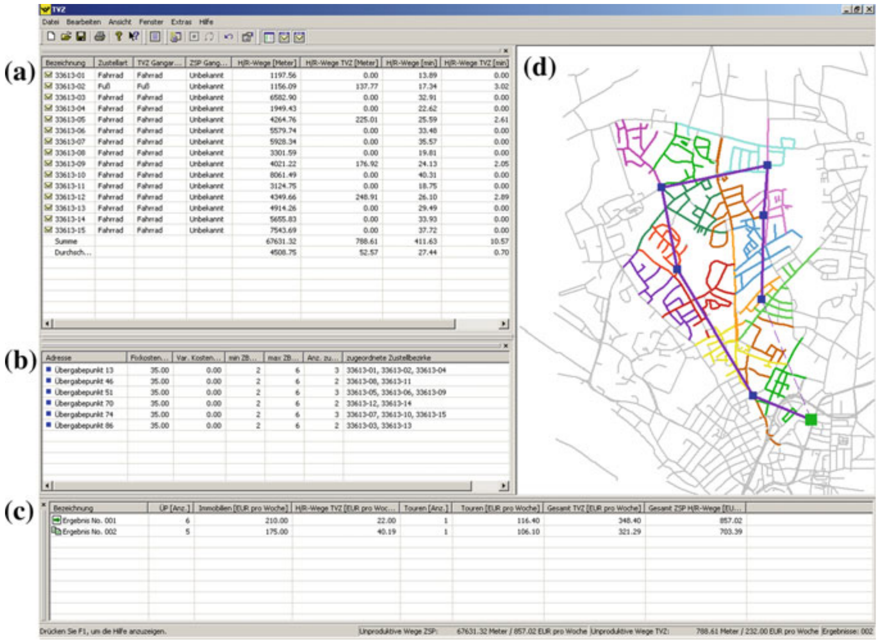


Fig. 12 Example scenario of deadheading reduction

The last area (Fig. 12d) is a visualization of the street network and delivery districts. Further, the selected transfer points are represented by small quadratic nodes and the DS is represented by a big quadratic node. The sequence of transportation tours from the DS is represented by connection lines, whereby the dashed line represents the return to the DS after the last visited TP on the tour. Moreover, the prototype can be used for scenario analysis. First, if there is no information available about potential transfer points, a set of potential transfer points is generated automatically on a grid pattern and shifted to the nearest node on the street network. The refinement of the grid pattern can be changed by the user if necessary. After the solution of this automatically generated scenario, local planners can retrieve information on where and how many TPs should be located. As mentioned above, transfer points are, e.g., car ports, whose availability at the locations suggested by the prototype has to be checked. In the majority this is not the case and, therefore, available transfer points close to the suggested ones must be found. After available potential transfer points are found and imported into the prototype, a new scenario can be computed and compared to the previous one(s). Furthermore, the prototype allows the user to manually insert potential transfer points and to shift them by their coordinates. An additional option window allows the user to fix transfer points, i.e. they have to be selected by optimization, or to change the default values of a_j and b_j individually. All described functionalities enable the generation and comparison of several different scenarios. This way, the prototype is a decision support system for retrieving information on where to search for suitable transfer points, where and how many to locate, and how to assign delivery districts to them. In addition, the prototype can be used to verify whether an already existing set of transfer points and its assignment of delivery districts is still optimal or at least a good solution. This is necessary in periodic cycles, because new potential transfer points could be available, or actual costs changes could occur.

Since 2006, the prototype has been applied to more than 4,000 delivery districts and Deutsche Post DHL has saved significant expenses by reducing deadheading on their postman tours.

5 Conclusion

The distribution networks in the postal logistics area are very complex. Therefore, decomposition into planning phases and subnetworks are necessary in order to optimize the distribution networks. In detail we have described three successful projects which have been executed by the Deutsche Post Chair of Optimization of Distribution Networks at RWTH Aachen University and by Deutsche Post DHL. These projects are examples of successful OR approaches in practice, consisting of problem analysis, algebraic optimization model development, solution of the optimization problems (using standard software tools or metaheuristics as well), and development of software prototypes. This paper does not only contain well known OR models and algorithms, but it also contributes to the development of methods and algorithms. In particular, it contains an approach to the multi-depot vehicle routing problem with restricted inter-tour resources, a location-routing approach for replanning problems by tabu search and a capacitated warehouse location-routing problem.

Each of the three projects was also successful from an economic point of view. Extensive costs savings were achieved by the replanning of the subnetworks described above using the three prototypes. At the same time the high service level was maintained.

References

1. Balinski ML (1965) Integer programming: methods, uses, computation. Manag Sci 12:253–313
2. Bräysy O, Gendreau M (2005) Vehicle routing with time windows, part I: route construction and local search algorithms. Transp Sci 39:104–118
3. Büdenbender K, Grünert T, Sebastian HJ (2000) A hybrid tabu search branch and bound algorithm for the direct flight network design problem. Transp Sci 34:364–380
4. Engelhard G, Grünert T, Sebastian HJ (1998) Thäringen M, Katz M, Kuchem R: Und ab geht die Post—Transportplanung für den Brieftransport der Deutschen Post AG. OR News
5. Grünert T, Sebastian HJ (2000) Planning models for long-haul operations of postal and express shipment companies. Eur J Oper Res 122:289–309

6. Hempsch C, Irnich S (2008) Vehicle-routing problems with inter-tour resource constraints. In: Golden BL, Raghavan S, Wasil EA (eds) The vehicle routing problem: latest advances and new challenges. Springer, New York, pp 421–444
7. Hermanns C (2009) Planung und Optimierung von Auslieferungsstandorten in komplexen Distributionsnetzwerken. Mainz Verlag, Aachen
8. Irnich S (2002) Netzwerk-Design für zweistufige Transportsysteme und ein Branch-and-Price-Verfahren für das gemischte Direkt- und Hinflugproblem. Dissertation, RWTH Aachen University, http://darwin.bth.rwth-aachen.de/opus3/volltexte/2002/300/pdf/Irnich_Stefan.pdf. Accessed 08 Nov 2013
9. Irnich S (2007) Resource extension functions: properties, inversion, and generalization to segments. OR Spectr 30:113–148
10. Irnich S (2008) A unified modeling and solution framework for vehicle routing and local search-based metaheuristics. Informs J Comput 20:270–287
11. Laporte G, Chapleau S, Landry PE, Mercure H (1989) An algorithm for the design of mailbox collection routes in Urban areas. Transp Res B-Methodol 23:271–280
12. Mechti R, Poujade S, Roucairol C, Lemarie B (1999) Global and local moves in tabu search: a real-life mail collection application. In: Voß S, Martello S, Osman IH, Roucairol C (eds) Meta-Heuristics: advances and trends in local search paradigms for optimization. Kluwer Academic, Boston, pp 155–174
13. Nagy G, Salhi S (2007) Location-routing: issues, models and methods. Eur J Oper Res 177:649–672
14. Pajunas A, Matto EJ, Trick M, Zuluaga LF (2007) Optimizing highway transportation at the United States postal service. Interfaces 37:515–525
15. Perl J, Daskin MS (1985) A warehouse location-routing problem. Transp Res B 19:381–396
16. Sebastian HJ (2012) Optimization in postal logistics. Presented at the INFORMS conference on applying science to the art of business, Miami, FL, http://meetings2.informs.org/Practice06/FINAL%20progPractice%20Conference%202006.pdf. Accessed 08 Nov 2013
17. Sebastian HJ (2012) Optimization approaches in the strategic and tactical planning of networks. In: Dolk D, Granat J (eds) Modeling for decision support in network-based services. Lecture Notes in Business Information Processing. Springer, Berlin Heidelberg, pp 36–61
18. Suhl UH (1994) MOPS—mathematical optimization system. Eur J Oper Res 72:312–322
19. Tarantilis CD, Kiranoudis CT, Markatos NC (2002) Use of the BATA algorithm and MIS to solve the mail carrier problem. Appl Math Model 26:481–500
20. Toth P, Vigo D (2002) An overview of vehicle routing problems. In: Toth P, Vigo D (eds) The vehicle routing problem. Siam, Philadelphia, pp 1–23
21. Toth P, Vigo D (2002) Branch-and-bound algorithms for the capacitated VRP. In: Toth P, Vigo D (eds) The vehicle routing problem. Siam, Philadelphia, pp 29–51