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Strategic Redesign of Urban Mail and Parcel Networks at La Poste

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We discuss our development of a decision model that allows La Poste, the French national postal operator, to assess the cost benefits of merging the urban mail and parcel delivery networks, which were run previously as separate entities. Our model, based on a mixed-integer linear program, derives the optimal network structure, including direct delivery, indirect delivery, or a hybrid structure, and provides an approximation of its routing cost. This approach allows us to model realistic large-scale problems. Based on data from the French city of Nantes, we find that merging the mail and parcel delivery networks yields cost benefits of approximately three percent, an amount that proves to be robust under various scenarios we tested. These findings corroborated La Poste management's expectations of potential cost savings and led to management's decision to create a new organizational structure in which local managers are responsible for the urban delivery of domestic mail and parcel.

Keywords: mail and parcel delivery networks; location-routing model; mixed-integer linear program; scenario analysis.

Urban Postal Delivery

For postal operators, the design of the delivery network for the various classes of items being transported, ranging from small envelopes to large packages, is of vital importance. The delivery network affects both the cost and the quality of delivery, where the latter may, for example, be measured in terms of delivery time windows. Although some postal operators (e.g., Deutsche Post in Germany) run a single network for a broad range of items to be delivered, others (e.g., PostNL in the Netherlands and Bpost in Belgium) operate separate networks for mail and parcel delivery. The design of the urban delivery network is strategically important as mail volume continues to decline as a consequence of electronic substitution, and small-parcel delivery can be expected to increase further with e-commerce and m-commerce as the major driver of this development. The total mail volume of the United States Postal Service (USPS) has declined by a compound annual rate of 1.4 percent (Marketline 2015) since 2010; similarly, the number of mail items La Poste handled decreased from 14.5 million in FY2012 to 13.7 million in FY2013, corresponding to a 5.6 percent decline (Marketline 2014). The growing online retail market was responsible for package-shipping revenue growth of about 9 percent for USPS in FY2014 (Marketline 2015).

The network of the future must therefore be robust with respect to possible shifts in item-size distribution and offer delivery-speed flexibility, particularly as same-day delivery becomes available in larger cities. Furthermore, newly introduced types of delivery options, such as automated parcel stations and pickup-point networks, both of which enable economies of scale in last-mile delivery, are growing quickly in size; thus, they may need to be incorporated into a modelling approach at a later stage (Morganti et al. 2014).

The team responsible for the assessment of urban network design alternatives at La Poste consisted of senior management in its mail division and experienced researchers. Management's overarching responsibilities were to develop cost-savings opportunities and prepare the organization for changes in mail and parcel delivery. One crucial aspect of this agenda was the potential, either partial or full, merger of the urban mail and parcel delivery networks. The researchers leveraged their expertise in operations research (OR) modeling, strategic and operational network optimization, and city logistics. Frequent communication and joint project meetings among all team members proved to be a prerequisite for success.

The Large-Scale Urban Network Design and Vehicle Routing Problem

Pickup and delivery of goods in an urban setting represent a key facilitator for future economic growth (Dablanc 2011), particularly as urban populations continue to grow; however, they typically cause detrimental effects, such as noise and emissions, eventually causing health and safety risks to the people living in these urban locations. This has fueled a persistently growing stream of academic literature related to city logistics (Crainic et al. 2009) to mitigate these kinds of externalities. On a more abstract level, urban-delivery network design can be categorized as a type of location-routing problem (Drexl and Schneider 2015, Winkenbach et al. 2016). In parallel, a number of city-logistics initiatives have been launched with mixed success thus far (BESTUFS II 2008). A solution to the urban-delivery and routing problem must address the strategic dimension in terms of number and type of facilities and their location; it must also address the operational dimension with respect to the deployment of different vehicle classes, ranging from vans to bikes, and their optimal routing based on an estimate of the demand that will materialize for mail and parcel delivery.

Because La Poste is the incumbent delivery service provider, its modelling environment must be sufficiently flexible to accommodate the existing infrastructure, such as intermediate depots for mail delivery that, because of the aforementioned e-substitution, might be reused for parcel storage. To ensure that our models would be useful for decision making within La Poste, we had to represent the city's geography with a sufficiently high level of detail and resolution. This led us to adopt a minimum city-segment area of 500×500 meters (m^2). A network in a medium-sized city (e.g., more than 100,000 inhabitants) would include a number of depots, vehicles, and delivery addresses that by far exceeds typical test instances for heuristics developed in the context of location and routing problems (Nguyen et al. 2012). Thus, a key requirement was to provide a useful approximation to the routing subproblem such that we could make our assessments in realistic settings; in our case, we used infrastructural data from Nantes, a French city of about 285,000 inhabitants. Moreover, the model's scalability had to be such that we could also evaluate the network in larger cities, such as Paris with its approximately 2.2 million inhabitants; in such a case, the optimal network structure will also consist of two echelons, with primary consolidation taking place at a small number of city distribution centers (CDCs) and secondary consolidation occurring at a larger number of intermediate depots (IDs). Our model will select either pure single-echelon or two-echelon network structures or a hybrid structure. As we mention above, postal operators, such as PostNL in the Netherlands, currently operate distinct networks for mail and parcel delivery; the model could be easily adjusted to analyze possible network mergers for PostNL, provided that the required input data, which we discuss below, are available.

We structured the remainder of this paper as follows. We review the existing literature in the *Searching for a Solution* section. *A Model for the Strategic Redesign of Urban Mail and Parcel Delivery* provides an overview of the location and routing model development. In *Model Results*, we discuss our findings from the various scenarios that we tested and discuss limitations of the current model. In *Benefits*, we report the total cost savings based on the project team's analysis and provide evidence of how the model results facilitated La Poste management's decision to merge the mail and parcel delivery networks. In *Lessons Learned*, we review key success factors of this project and conclude the paper.

Searching for a Solution

Two possible modelling directions emerged from our literature search. We might have formulated the problem as an instance of capacitated clustering problems

(CCPs). The CCP, applied to network design, is based on the concept of partitioning the locations of pickup and delivery into a minimum number of clusters, which can then be served by a single capacitated vehicle under a time constraint; this constraint could be either the length of a working day or a shorter service time window. Laporte et al. (1989) formulate the problem of postal route formation as a CCP. More recently, Bard and Jarrah (2013) apply this approach to analyze whether commercial and residential pickup and delivery networks should be operated separately or merged either partially or wholly in the pursuit of cost savings. Vanderbeck (2000) finds a solution for the large mixed-integer problem by using column generation based on Dantzig-Wolfe decomposition. Although the approach Bard and Jarrah (2013) propose is capable of dealing with large problem instances of up to 50,000 demand locations, they need to restrict themselves to a single-echelon network structure and a fleet of homogeneous vehicles. Allowing for up to two echelons and for a heterogeneous fleet that ranges from bikes to vans is a crucial prerequisite in the current application at La Poste.

This led us then to consider the location-routing-problem (LRP) literature in which the two-echelon location-routing problem (recall that the two echelons refer to primary and secondary consolidation, respectively) has been addressed in the context of city logistics (Crainic et al. 2009, 2011). Exact and heuristic solutions, which accommodate capacitated distribution centers at both echelons and explicitly solve the vehicle routing problem, have been proposed. However, only instances of up to five distribution centers in the first echelon, 20 intermediate depots, and 200 delivery locations can thus be solved. Because this instance size was clearly insufficient for our modelling purposes, particularly because of the number of delivery locations, we decided to replace the explicit vehicle routing step by approximating the routing cost. The routing cost is given by the transportation cost from a facility to and within a demand cluster, which is a function of the number of demand locations served, the density of these demand locations, and the average distance between the facility and the demand locations. Daganzo (2005) pioneered this approach of cost approximation without explicit vehicle routing; Winkenbach et al. (2016) enhanced it to also capture item handling cost and vehicle operating costs in the presence of heterogeneous fleets. Winkenbach et al. (2016) solve large problem instances; therefore, this work represents a suitable basis for modeling La Poste's mail and parcel network merger. However, we had to implement two key extensions to account for the two network structures that initially coexisted because the mail network often consisted of one distribution center (first echelon) and a number of intermediate depots (second echelon), whereas the parcel network consisted of two distribution centers (first echelon only). We needed to be able to allow for more than one distribution center and also for hybrid delivery structures (i.e., structures that, within one network, accommodate making some deliveries via the intermediate depots and other deliveries directly from the distribution center). We note that the design of *national* postal networks is also frequently addressed in the research, where the emphasis is put on optimal design of either pure hub-and-spoke or hybrid hub-and-spoke systems; the latter also includes direct deliveries. Lee and Moon (2014) solve Korea Post's national transportation problem, which involves one exchange center as the hub and 25 mail-processing centers.

We believe that the following aspects characterize the originality of our work. First, we provide a modelling environment that allows for a level of granularity that faithfully reflects both the mail and the parcel networks. Thus, we accurately captured the initial situation (i.e., the separate operation of the mail and parcel networks); this proved to be important for obtaining management's acceptance of the model. In our analysis, we began by adding an increasing number of parcels, based on their sizes; we added smaller items first, thus allowing us to study the optimal networks for 0-percent and 100-percent integration of parcels into the mail network. The model that we developed is grounded in real data, which we derived or triangulated primarily from La Poste's current mail and parcel operations. This enabled us to validate critical elements of the model and the ensuing recommendations. Second, the model's architecture is such that additional infrastructural elements, which may become relevant in the years to come (Ducret 2014) can be incorporated in a straightforward manner; examples might include automated parcel stations or pickup-point networks, a broader range of delivery vehicles (e.g., drones), or additional constraints imposed by environmental regulations.

A Model for the Strategic Redesign of Urban Mail and Parcel Delivery

The basis for our model development is Winkenbach et al. (2016) who present a mixed-integer linear programming (MILP) model, which solves a large-scale two-echelon location-routing problem. The two echelons refer to the level of the CDCs and the level of the smaller IDs, respectively. The model allows for mixed heterogeneous fleets, ranging from vans to pedestrian delivery, storage facilities, and all types of delivery vehicles, which we characterize by capacity limits. The objective function (the appendix provides the mathematical details) minimizes the total cost, which comprises handling, operational vehicle, transportation, and facility fixed costs.

To account for various geographical constraints (e.g., rivers) in the design of the optimal distribution system and to accommodate nontrivial spatial demand distributions, we divide the city area into a large number of square city segments of 500×500 m^2, which we subsequently consider individually to calculate the cost of serving the points of demand (PODs) contained within their respective boundaries. We describe each city segment by a set of parameters that define its geographic location (i.e., GPS coordinates and the corresponding demand characteristics). We assume that PODs are uniformly distributed within each segment, which then enables us to apply continuous approximation techniques for the routing cost (Daganzo 2005). We can justify this assumption for city segments, such as Nantes, that have fairly homogeneous building types; however, we might have to revisit this assumption for less heterogeneous city segments, such as those that have both tall towers and smaller buildings.

The model allows vehicle types to differ in both their physical and economic properties. Each vehicle type can be assigned two average speeds for travel within pickup and delivery tours and for travel on line-haul distances; in addition, vehicle types can be assigned space requirements for parking, sorting, and loading. Vehicles differ in their carrying capacity, ranging from 160 liters (small cargo bikes) to 2,500 liters (small vans). For each vehicle type, we estimate, based on existing La Poste data, a tour setup time, per-item loading and unloading times, and average service times per stop and per item. Furthermore, we account for the hourly operations cost, drivers' wages, and the daily fixed cost. In the continuous-routing cost approximation, we can specify a detour factor for each vehicle; this reflects the extent to which the actual distance a vehicle must travel between two given locations differs from the corresponding Manhattan distance, which represents the sum of horizontal and vertical displacements in the grid-like street structure in the New York City borough of Manhattan. Thus, we attribute a factor of 0.8 to a bicycle because it allows us to find shortcuts within narrow city-center streets, and a factor of 1.15 to vans (Daganzo 2005) because of the necessary detours they must take.

We extend the model proposed in Winkenbach et al. (2016) with respect to admissible network structure and to the modelling of the joint distribution of item sizes and number of items per stop. Thus, we allow for (1) facility networks with multiple CDCs, and (2) any distribution network to take the structure of pure direct delivery (i.e., via CDC), pure indirect delivery (i.e., via CDC and ID), or a hybrid delivery system in which some city regions are served via direct delivery and others via indirect delivery. In the *Results* section below, we report that all three cases occur.

When parcel items (ranging in size from 3,000 to 25,000 cubic centimeters (cm^3)) are merged with mail items (ranging in size from 80 to 680 cm^3) for delivery, this transforms the previously unimodal distributions of both item classes, when considered separately, into a distribution of item sizes that exhibits two modes. Based on the probability distribution for the number of items per stop, which we estimated from La Poste's historical data, and the probability distribution of the physical size of mail and parcel items, we employ Monte Carlo simulation to determine the joint probability distribution for the physical volume of all items to be delivered at any given stop.

We use this extended model to assess the potential cost advantages of merging La Poste's previously separate distribution networks for mail and parcel items:

initially, we separately determine the optimal network structure for mail and parcel operations. Then, we gradually merge item volumes from the parcel network into the mail network, starting with the smallest parcels. For a given threshold of parcel sizes, we recompute the optimal network designs for the resulting mail network by adding small parcels (up to the threshold size); the resulting parcel network delivers only parcels above the threshold size. We continue until we have merged all parcels into the mail network. Based on the total cost of both networks, we derive the optimal degree of network consolidation.

Model Results

We use scenario analysis to investigate the effects of trends, both internal and external to the company, and influences on the optimal parcel volume transfer. From the perspective of internal trends, we study various scenarios in which alternative vehicle technologies (e.g., cargo bikes, electric vans) are available for use in delivery operations. We also study the effect of various levels of company-defined delivery service quality, measured by the speed of delivery. From the perspective of external trends, we focus our analyses on changes expected in the near future in the overall mail and parcel volume to be served, on potential shifts in the item-size distribution of parcel volumes, and on temporary parcel demand peaks (e.g., peaks encountered prior to Christmas). These analyses allow us to evaluate the robustness of corresponding management decisions to company-internal trends and developments and to external changes in the marketplace.

We find that the maximum cost savings range, across scenarios, between 3 percent in the base case to 7 percent in the e-commerce case, which includes a greater number of parcels. We observe that a complete merger of parcel items into the mail network is optimal.

The Base Case

The base case scenario represents the current status quo of La Poste's mail and parcel delivery operations for the city of Nantes. Therefore, we use it as the reference point for our analyses and make the following assumptions:

- available vehicle types and capacities: pedestrians with trollies (maximum capacity 120 liters), medium-size cargo bikes (600 liters), and small vans (2,500 liters);
- maximum service time allowed for one trip: four hours;
- mail volume and size: approximately 525,000 items at 140,000 stops, historic La Poste item-size distribution between 80 and 680 cm^3 with a mean of 215 cm^3, historic La Poste distribution for items per stop;
- parcel volume and size: approximately 13,000 items at 9,000 stops; expected item size: 12,600 cm^3; historic La Poste item-size distribution between 3,000 and 25,000 cm^3; historic La Poste distribution for items per stop;
- facilities: Four potential CDC locations and 68 potential ID locations.

For the base case, we find a cost-optimal solution for a complete merger of La Poste's parcel volumes into the mail network (Figure 1) that reduces

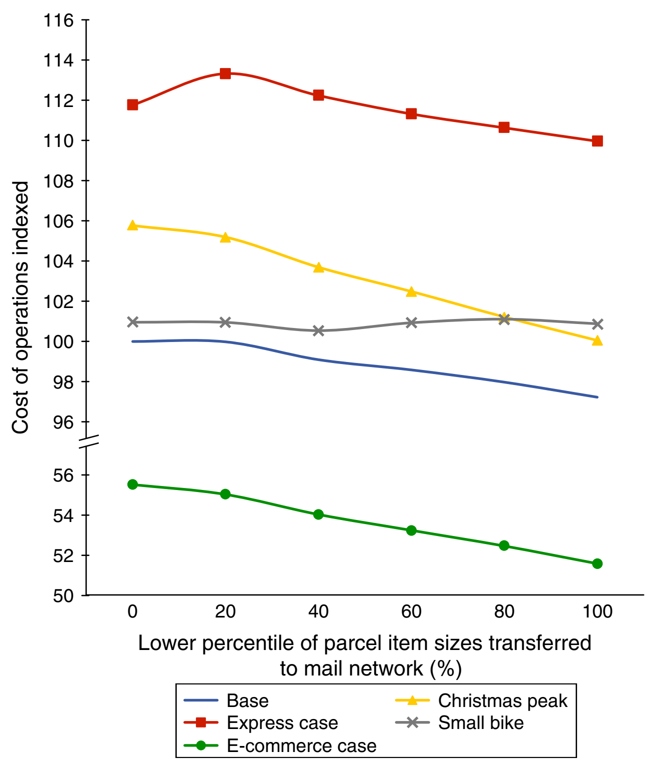

Figure 1: (Color online) The total cost curves indicate that for all but one scenario, a full merger of mail and parcel networks yields the lowest cost. Note that total daily costs are indexed, where the base case with two separate networks represents 100.

the operating costs by 3 percent. A partial merger, which sacrifices some of the savings, would offer La Poste the flexibility to adapt to changing demand patterns, volumes, and item sizes, which having two separate, but jointly managed, networks would provide. In our model, we do not quantify the value of such flexibility, which we might evaluate from a real options perspective (real options is a modeling approach that allows us to quantify managerial flexibility using financial option valuation as an analogy); therefore, we do not reflect this in the total cost curves depicted in Figure 1.

When analyzing the model results for the base case with respect to fleet composition and infrastructure (Figure 2), we observe that prior to the consolidation of any parcel volume with the mail network, the model suggests a single-echelon network design in which parcel delivery is operated from a single CDC. For mail delivery, the model suggests single-echelon operations out of two CDCs for 67 percent of the city area, but a two-echelon system that initially uses 14 IDs for the remaining part of Nantes. When the parcel volumes are merged with the mail network, the number of IDs decreases to six. Prior to merging any parcel volumes into the mail network, vehicles for mail delivery are clearly dominated by cargo bikes (1,644) with a sizable number of pedestrians (499), while parcel delivery is dominated by vans (197). As parcel volumes are merged into the mail network, the pedestrians are replaced by bikes and vans for the greater share of parcels. As merged parcel volumes increase, the number of vans used in the network decreases from its initial value of 203 to 55. Thus, merging the two networks provides cost savings and also reduces particulate matter and CO_2 emissions.

Figure 3 (0-percent merger) and Figure 4 (100-percent merger) show a map of Nantes, including the $500 \times 500\ m^2$ segments we introduced for our analysis.

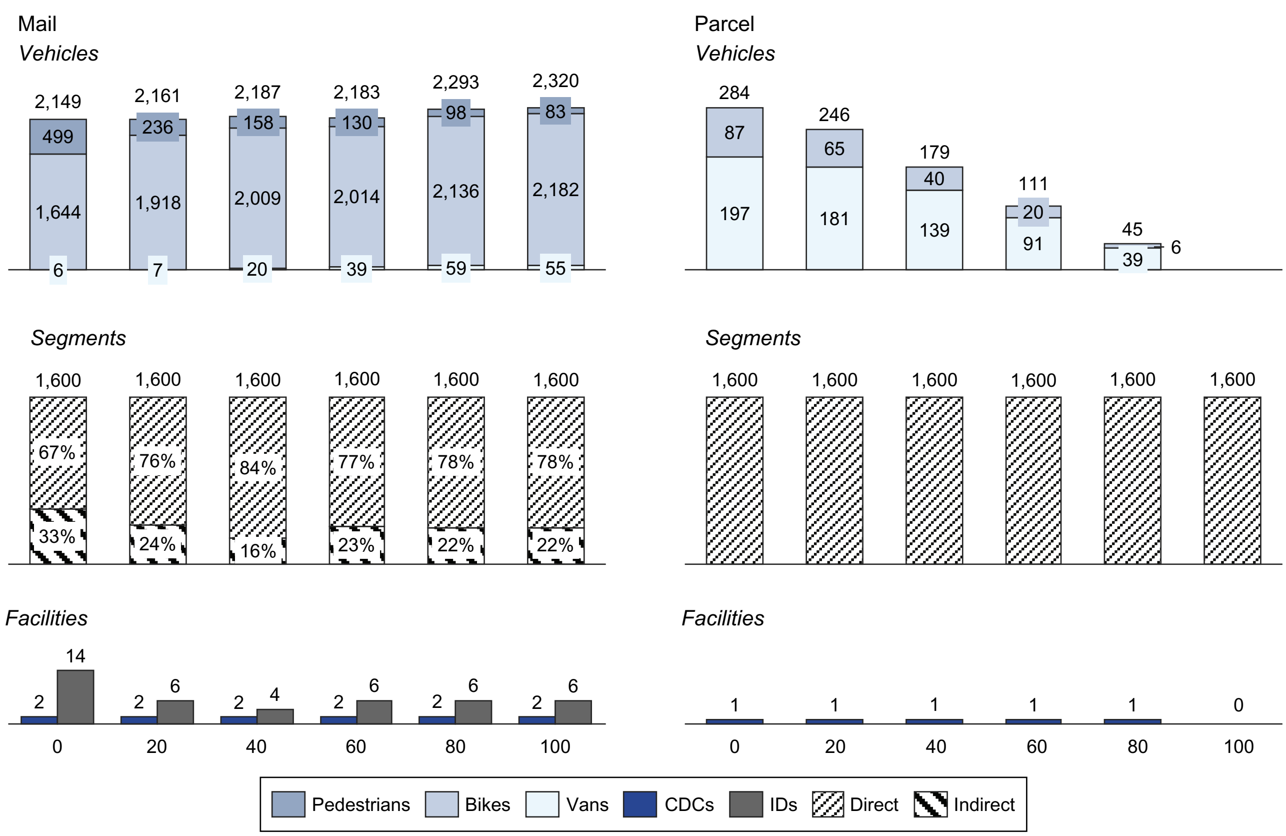

Figure 2: (Color online) The vehicular fleet composition and depot structure for the two networks are dependent on the degrees of mergers, which we indicate here for the base case scenario.

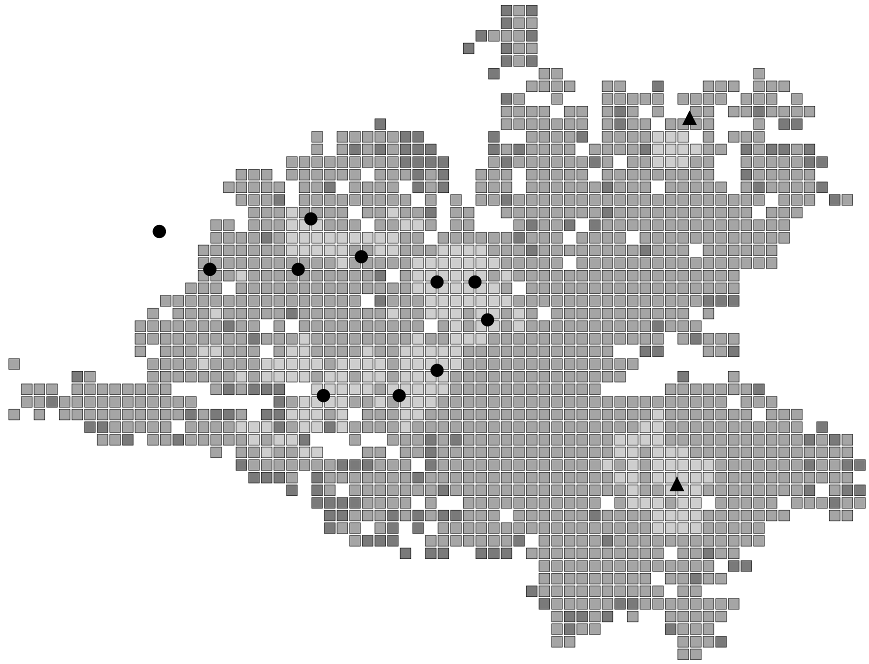

Figure 3: The map depicts the city of Nantes with the 500×500 m^2 segments for analysis in the case with two separated networks. We indicate pedestrian usage by light shades, bike usage by medium shades, and van usage by dark shades. We represent IDs by circles (14 in total, 11 of which are visible in the map) and CDCs by triangles.

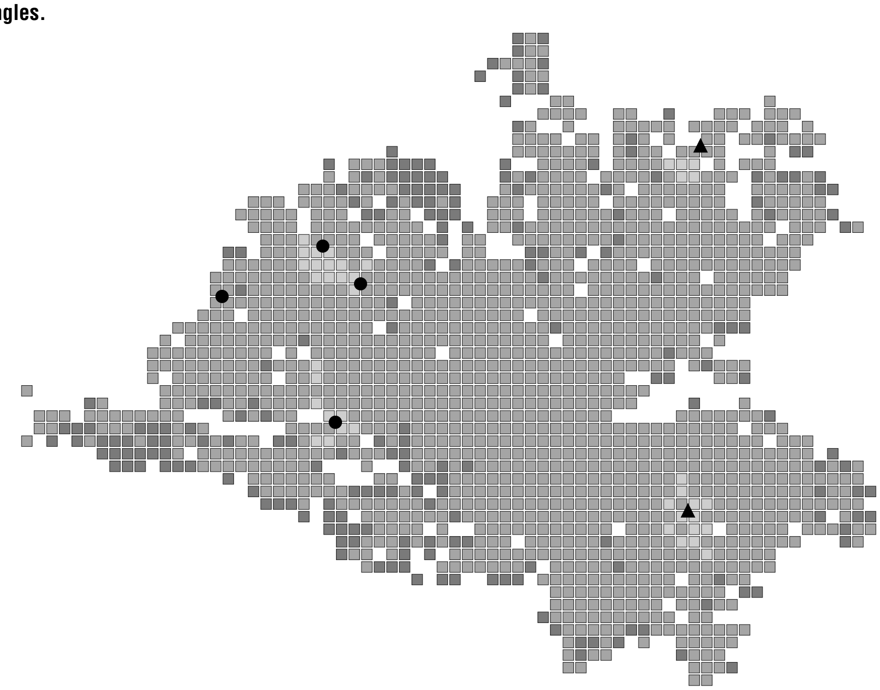

Figure 4: The map depicts the city of Nantes with the 500×500 m^2 segments for analysis in case of one fully merged network. We indicate pedestrian usage by a light shade, bike usage by a medium shade, and van usage by a dark shade. We represent IDs by circles (six in total, four of which are visible in the map) and CDCs by triangles.

The figures illustrate the shift in vehicle usage and the reduced number of depots as the two networks are merged.

Growth of E-Commerce

The postal industry expects parcel volumes to increase considerably during the next few years as a result of a rapid expansion in e-commerce and m-commerce, and expects mail volumes to continue to decline. To understand the impact of such a development on the recommendations derived from our model, we analyzed a scenario that captures this expected growth in e-commerce. We altered the assumptions in the base case as follows: mail volume declines to 262,500 items (i.e., decreases by 50 percent) at 70,000 stops, whereas parcel volume increases to 15,500 items at 10,700 stops.

For the complete merger, we observed cost savings of 7 percent. Compared to the base case, our observations for the e-commerce case differed as follows. The merged network kept the structure that relies on CDCs and IDs; however, the number of IDs decreased from eight to two when parcel items were merged into the network.

Christmas Peak

A crucial aspect of network design for postal operators is the network's ability to cope with demand peaks prior to a singular event such as Christmas. To simulate this scenario and understand its implications on the network merger decision, we analyzed a scenario in which we increased the parcel volume to 26,000 items at 18,000 stops.

In our simulation, we attained cost savings of 5 percent for the total merger. In terms of network design and vehicular fleet compositions, our findings for the Christmas peak case were broadly in line with the base case. Only the number of vans required increased as a result of the larger overall volume of parcels.

Shorter Delivery Time Windows

With increasing expectations of both consumers and (online) retailers with regard to delivery quality, time-window delivery, and same-day delivery, the attainment of shorter global service times has become increasingly important to postal operators. Amazon is currently testing one-hour time windows in the New York City borough of Manhattan; therefore, shorter time windows might become the norm in the future. To understand the effect of shorter global service times on the network merger decision, we analyzed a scenario with a two-hour (rather than four-hour) time window.

We can observe a cost minimum, which yields cost savings of about 2 percent, for the full merger. As expected, the overall total cost is significantly higher than the cost for the base case; this reflects the additional cost incurred from adhering to a shorter global maximum service-time constraint (Figure 1). Moreover, we can see that the model suggests a partial two-echelon network design for mail delivery both prior to the merger of any parcel volumes into the mail network and when the merged parcel volume increases. The mail network starts off with two CDCs and 36 IDs prior to any consolidation of parcel volume with the mail network. For a complete network merger, the number of CDCs increases to three and the number of IDs decreases to 24. Interestingly, when only 20 percent of the mail items are merged into the network, the total costs *increase* as compared to the base case, because the cost increase in the mail network is more significant than the accompanying cost savings in the parcel network.

We see that vans are the dominant vehicle type for both direct mail and direct parcel delivery, while bikes are predominantly used for indirect mail delivery. Notably, for the 0-percent merger, a relatively large number of pedestrians (1,435) is used for mail delivery; this number drops to 900 for the 20-percent merger and decreases further to 785 for the complete merger. Thus, the number of pedestrians used remains at higher levels than in the previous scenarios.

Small Cargo Bikes

All our previous analyses have been based on the assumption that a relatively large cargo bike (600 liters) is available to La Poste for its mail and parcel delivery in Nantes. Adjusting the size of the cargo bike to 160 liters, we decided to test whether our recommendations would change if a significantly smaller postal bike were available.

As Figure 1 shows, the smaller carrying capacity of bikes has an effect on the overall cost of delivery operations, because the savings stemming from the merger essentially disappear. However, bikes are no longer used in parcel delivery. In addition, for mail delivery, the number of bikes used is significantly smaller than in the base case, and the number of vans used in the merged network increases. Thus, the benefit of a smaller carbon footprint for delivery operations can only be achieved by using the larger bikes.

Limitations of the Model

In the strategic design of the urban delivery network, we assumed that total cost minimization was the primary objective. We can justify this on the grounds of the universal service obligation and regulated postal tariffs. However, in the future, La Poste might face a situation in which lowering its carbon footprint related to delivery activities becomes more important, possibly requiring the formulation of an overall emission constraint. Although we do not currently implement such a constraint in the model, we could add it at a low cost. As Figure 2 indicates, a higher degree of merging the two networks is accompanied by a lower number of vans, resulting in lower emissions. La Poste currently runs about 10,000 electric vehicles; had we considered these vehicles, overall emissions would have been reduced further.

Benefits

The model developed within this research project has a spreadsheet-based user interface, whereas we solved the mixed-integer linear program in the appendix using Gurobi in a Python environment. Within the spreadsheet, the user may specify infrastructural and vehicle-related data and provide the source for the geographic coordinates of distribution centers, depots, and points of delivery. This structure proved highly beneficial because it allowed La Poste's management to design and test scenarios that it deemed to be of particular relevance and to also explore the rationale for merging mail and parcel delivery in Angers and Paris—not only in Nantes, the city we considered in this study. Managers and specialists at La Poste were familiar with spreadsheet-based modelling; therefore, they were able to readily use the tool we provided. The use of the Gurobi solver enabled us to scale the initially smaller instances to ones that were necessary for realistic setups in cities with hundreds of thousands of inhabitants. In addition, using the Gurobi solver enabled us to quickly obtain results; this facilitated discussion and the associated feedback, particularly in the early phases of the project. Thus, we could capture the correct level of detail of postal operations within cities.

We conducted our initial discussions on potential synergies between mail and parcel delivery within all cities within La Poste's domain; this represented a significant deviation from the course followed during the previous 15 years: the organization of La Poste had been based on four independent divisions (i.e., bank, retail, parcel, and mail). Each autonomous division had developed its own products and services, its own territorial organization, and its own processes. One advantage of this structure of independent divisions is that the respective teams could focus on their own processes and related investments, thus fostering responsibility for their own revenue.

However, because of the declining mail business resulting from the electronic substitution, which has further increased over the past four years, La Poste management was starting to doubt the profitability of its mail process. Cost analysis is a critical issue when the fixed costs are high and marginal cost low, as is the case for mail delivery. The mail and parcel divisions had always had an agreement for the delivery of the mail and parcels in rural areas. The fixed cost of delivering to these areas by car, whose capacity is sufficient to transport the mail and the parcel for the same routes, represents the majority of the total costs; in the cities, however, the two deliveries were independent and the management of each division was autonomous.

To overcome organizational barriers, La Poste's ability to demonstrate that cost savings would accrue by merging mail and parcel operations in cities was of utmost importance. To gain credibility, such a demonstration had to be based on a model that reflects realistic environments and cities with large population sizes. Existing models within La Poste were geared toward optimizing the mail delivery *or* parcel delivery, but not a combination of both.

Thus, the proposed model's capability to design a single- or two-echelon delivery network for a given percentage of parcel items added to the mail network was of crucial importance. Our simulation runs allowed us to propose a new organization with merged urban mail and parcel delivery. The types of vehicles, the number of depots, and the existing or future traffic patterns were important parameters in the model.

For La Poste, another crucial aspect of this study related to the question of how the methodology that we proposed for the analysis of the city of Nantes would scale up for larger cities, such as Lyon or Paris. From a methodology point of view, scalability is possible because we could partition larger areas into smaller ones with, for example, up to five CDCs and 200 IDs, which is an instance size that we could simulate in less than 24 hours. However, Paris represents some challenges for the current model, because it exhibits a higher propensity for traffic jams and has a number of streets in which vans are banned; we cannot explicitly model these factors using our approach.

The results of our modelling approach have convinced La Poste management that a merger of mail and parcel delivery will provide cost savings of approximately 3 percent. This cost advantage can be achieved, as we demonstrate above, by enlarging the fleet of bikes and reducing the number of vans. Because vans face a greater risk of being stuck in traffic, in particular on narrow inner-city streets, this new fleet composition may entail further benefits that we did not quantify in this study. Such effects could be quantified by representing inner-city traffic by a queueing network. However, the merger and the associated cost savings apply to urban areas only, because in rural areas, as we note above, the two networks already run jointly.

To ascertain the efficiency of the operational merger, in mid-2014, La Poste implemented a new organization for its French domestic operations, incorporating a single division for the mail and the parcel markets and local managers in charge of the delivery of mail and parcel for any type of location. The changes suggested by the model (i.e., the merger of the two operations and the ensuing changes in vehicular fleet and depot infrastructure) are currently being implemented in Nantes (285,000 inhabitants), Angers (150,000 inhabitants), and other cities. Although La Poste management understand the cost advantages, negotiations with the stakeholders, such as drivers and depot personnel, are fairly complex; for example, routes with the larger parcels are now scheduled in the late afternoon to increase the probability of being able to deliver the parcels, thus further reducing cost; however, this entails longer working hours for the delivery personnel.

Verifying the savings that our model predicted is complicated because implementing the merger will take about six months; during this time, volume and delivery points may change, and postal personnel demographics and absenteeism may change as a result of factors such as retirement, thus rendering a reliable cost-savings estimate difficult. One indicator is the number of employees in the mail and parcel operations of the cities in which the merger has been implemented. In Angers, this number was lower; however, entirely attributing this to the organizational change would require further analysis.

Lessons Learned

A principal lesson that La Poste's management learned from this project relates to the robustness of the merged mail and parcel delivery in cities. In all cases, merging the two networks provided cost advantages. This was true whether small or large bicycles were employed (although the cost savings were very small in the case of small bikes), whether the number of parcels increased as an expected consequence of a rising share of online business, or whether shorter time windows were applied in an effort to raise service quality. This robustness was somewhat unexpected even by experienced managers within the mail division. The role of OR in the strategic transformation of merging mail and parcel delivery networks was evident. An OR model, comprising a user-friendly interface, an optimization engine that is built on an approach anchored in the academic literature, and the necessary extensions to accurately depict the decision problem at hand, provided a convincing basis for management's decision.

Equally important, however, was that La Poste's managers involved in this project were able to communicate effectively with the team of researchers regarding the functionality required, provision of data, discussions of initial test runs, model improvements, and analysis of results, and to also succeed in translating the model's results into managerial action and organizational transformation. The model can be easily extended to, for example, capture a network of pickup points, other than household addresses, for final delivery. To accomplish this, La Poste purchased a company, Pickup, in 2009 (Morganti et al. 2014) and currently bundles La Poste and Pickup express mail activities. In the future, La Poste might conceivably integrate this company into its mail and parcel network. To conclude, the model's usage at La Poste is clearly not limited to this single implementation; the company plans to apply it for network extensions and mergers in the future.

Appendix. Mathematical Details

The following mixed-integer linear programming (MILP) model optimizes the total cost of serving a given demand within a city over discrete-choice active facility locations on two levels (city distribution centers (CDCs) and intermediate depots (IDs)) and the allocation of city segments to facilities. Here, we summarize the notation of this model.

A_i: Physical size of demand area i.
$c^{\text{hand-CDC}}$: Per-item handling cost at CDCs.
$c^{\text{hand-DEP}}$: Per-item handling cost at IDs.
$C^{\text{real}}_{dijk^{\text{D}}k^{\text{P}}}$: Real carrying capacity, measured in number of stops, of a vehicle of type j serving demand area i from ID location d, taking into account the global service time constraint, if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
c^{space}_d: Rent level (EUR/m^2/day) at ID or CDC location d.
$C^{\text{stops}}_{ijk^{\text{D}}k^{\text{P}}}$: Carrying capacity of vehicle type j, measured in number of stops, when serving demand area i if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
c^{veh}_j: Hourly cost of operation (e.g., fuel, wear, maintenance) for vehicle type j.
C^{vol}_j: Carrying capacity of vehicle type j, measured in physical volume (e.g. cm^3).
f^{CDC}: Daily fixed cost of CDCs.
f^{DEP}: Daily fixed cost of IDs.
f^{veh}_j: Daily fixed cost (e.g., depreciation, insurance) for vehicle type j.
$\mathbf{K}^{\text{D}}_i$: Set of potential values for the aggregate physical volume of delivery items at a stop in demand area i.
$k^{\text{D}} \in \mathbf{K}^{\text{D}}_i$: Volume class index (delivery).
K^{fac}: Total facility fixed cost.
K^{hand}: Total handling cost.
$\mathbf{K}^{\text{P}}_i$: Set of potential values for the aggregate physical volume of pickup items at a stop in demand area i.
$k^{\text{P}} \in \mathbf{K}^{\text{P}}_i$: Volume class index (pickup).
K^{space}_{dij}: Cost of rent for all the space needed by vehicles of type j serving demand in demand area i from ID d.
K^{space}_{cij}: Cost of rent for all the space needed by vehicles of type j serving demand in demand area i from CDC c.
k^{tour}: In-tour Daganzo factor (Daganzo 2005).
$K^{\text{1-E}}_{cij}$: Cost of serving demand area i with vehicles of type j on a single-echelon network with goods being shipped from CDC c.
$K^{\text{2-E-E1}}_{dij}$: Cost of the first transport echelon when serving demand area i with vehicles of type j on a two-echelon network with goods flowing through ID d.
$K^{\text{2-E-E2}}_{cdj}|_{j=j^{E2}}$: Cost of the second transport echelon when shipping all the demand served on a two-echelon network with goods flowing through ID d from CDC c. Note that the vehicle type for second-echelon transportation is fixed to j^{E2} here.
$\mathbf{L}^{\text{CDC}}$: Set of available locations to position an active CDC.
$c \in \mathbf{L}^{\text{CDC}}$: CDC index.
M^{big}: Big number.
$m^{\text{tours}}_{dijk^{\text{D}}k^{\text{P}}}$: Number of tours effectively started by a vehicle of type j serving demand area i within the global service time window if it is based at ID location d, and if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
$n^{\text{runs}}_{dijk^{\text{D}}k^{\text{P}}}$: Number (fraction) of full-capacity tours a vehicle of type j can effectively perform in demand area i within a global service time window of length T^{E1} if it is based at ID location d, and if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
$n^{\text{stops}}_{dijk^{\text{D}}k^{\text{P}}}$: Number of stops made per tour by a vehicle of type j serving demand area i within the global service time window if it is based at ID location d, and if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
$q^{\text{veh}}_{cijk^{\text{D}}k^{\text{P}}}$: Number (fraction) of vehicles of type j needed to serve demand in demand area i from CDC or ID location c if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
$q^{\text{2-E-E2}}_{cd}$: Number (fraction) of vehicles (of type j^{E2}) needed to ship items from CDC c to ID d in a two-echelon network.
r_{di}: Euclidian distance between ID location d and demand area i.
s^{haul}_j: Line-haul speed of vehicle type j.

s_j^{tour}: In-tour speed of vehicle type j.
$S_{cij}^{\text{1-E}}$: Binary decision variable; a value of 1 indicates that demand area i is served on a one-echelon network using vehicle type j with goods being shipped from CDC c.
$S_{cdij}^{\text{2-E}}$: Binary decision variable; a value of 1 indicates that demand area i is served on a two-echelon network using vehicle type j on the first transport echelon with goods originating from CDC c and flowing through ID d.
$t_{ijk^{\text{D}}k^{\text{P}}}^{\text{capa}}$: Time required to perform a full-capacity tour (neglecting any time constraint) in demand area i with a vehicle of type j if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
T^{E1}: Global maximum allowed service time for first-echelon transportation.
t_{dij}^{haul}: Time required to overcome the line-haul distance between ID location d and demand area i with a vehicle of type j.
k^{haul}: Line-haul Daganzo factor (Daganzo 2005).
t_j^{item}: Per-item incremental additional service time of vehicle type j.
$t_{ijk^{\text{D}}k^{\text{P}}}^{\text{load}}$: Time required to fully load a vehicle of type j serving demand area i (neglecting any time constraint) if the physical volume of pickup items at each stop falls into volume class k^{P} and the physical volume of delivery items at each stop falls into volume class k^{D}.
t_j^{setup}: Fixed setup time per tour required by vehicle type j.
t_j^{stop}: Per-stop base service time of vehicle type j.
$t_{ij}^{\text{stop-det}}$: Time required by vehicle of type j to overcome average interstop distance and come to a halt at a stop in demand area i.
$\mathbf{V}$: Set of available vehicle types.
$j \in \mathbf{V}$: Vehicle type index.
w_j: Wage cost for vehicle type j.
$\mathbf{W}$: Set of demand areas to be served.
$i \in \mathbf{W}$: Demand area index.
X_c^{CDC}: Binary decision variable; a value of 1 indicates that an active CDC is positioned at CDC location c.
X_d^{DEP}: Binary decision variable; a value of 1 indicates that an active ID is positioned at ID location d.
γ_i: Density of stops in demand ares i.
Δ_i^{D}: Discrete random variable; size of a delivery item at a stop in demand area i.
$\hat{\Delta}_{k^{\text{D}}}$: Size of items belonging to delivery item size class k^{D}.
Δ_i^{P}: Discrete random variable; size of a pickup item at a stop in demand area i.
$\hat{\Delta}_{k^{\text{P}}}$: Size of items belonging to pickup item size class k^{P}.
ρ_i: Average number of items per stop in demand area i.
$\bar{\zeta}_c$: Space capacity (for accommodating vehicles) of ID or CDC c.
ζ_j^{space}: Space requirement of vehicle type j for parking, sorting, unloading, and loading.

Acronyms
2E-CLRP: Two-echelon capacitated location-routing problem.
APS: Automated package station.
PEP: Product exchange point.
SOS-1: Special ordered set type 1.
ARCE: Augmented routing cost estimation.
EC: E-commerce or electronic commerce.
GMST: Global maximum service time.
MST: Maximum service time.
MILP: Mixed-integer linear programming.
MIP: Mixed-integer programming.
ULS: Urban logistics services.
ICE: Internal combustion engine.
PO: Postal operator.
USO: Universal service obligation.
UGT: Urban goods transportation.
CDC: City distribution center.
ID: Intermediate depot.
GDP: Gross domestic product.
LRP: Location-routing problem.
VRP: Vehicle routing problem.
CVRP: Capacitated vehicle routing problem.
CFLP: Capacitated facility location problem.
MDVRP: Multidepot vehicle routing problem.
2E-CVRP: Two-echelon capacitated vehicle routing problem.
CLRP: Capacitated location-routing problem.
POD: Point of demand.
RLE: Route length estimation.
EV: Electric vehicle.
TS: Tabu search.

Objective Function and Constraints

$$\min_{S_{cdij}^{\text{2-E}}, S_{cij}^{\text{1-E}}, X_c^{\text{CDC}}, X_d^{\text{DEP}}} \Bigg\{ \sum_{c\in\mathbf{L}^{\text{CDC}}} \sum_{i\in\mathbf{W}} \sum_{j\in\mathbf{V}} \Bigg(\sum_{d\in\mathbf{L}^{\text{DEP}}} S_{cdij}^{\text{2-E}} \big(K_{dij}^{\text{2-E-E1}} + K_{dij}^{\text{space}}\big) + S_{cij}^{\text{1-E}} \big(K_{cij}^{\text{1-E}} + K_{cij}^{\text{space}}\big) \Bigg) + K^{\text{hand}} + K^{\text{fac}} + \sum_{c\in\mathbf{L}^{\text{CDC}}} \sum_{d\in\mathbf{L}^{\text{DEP}}} K_{cdj}^{\text{2-E-E2}}\big|_{j=j^{E2}} \Bigg\} \tag{1}$$

subject to

$$\sum_{c\in\mathbf{L}^{\text{CDC}}} \sum_{j\in\mathbf{V}} \Bigg(\sum_{d\in\mathbf{L}^{\text{DEP}}} S_{cdij}^{\text{2-E}} + S_{cij}^{\text{1-E}} \Bigg) = 1 \qquad \forall i \in \mathbf{W}, \tag{2}$$

$$\sum_{c\in\mathbf{L}^{\text{CDC}}} \sum_{j\in\mathbf{V}} S_{cdij}^{\text{2-E}} \le X_d^{\text{DEP}} \qquad \forall d \in \mathbf{L}^{\text{DEP}},\ i \in \mathbf{W}, \tag{3}$$

$$\sum_{j\in\mathbf{V}} S_{cij}^{1\text{-E}} \le X_c^{\text{CDC}} \qquad \forall c\in\mathbf{L}^{\text{CDC}},\, i\in\mathbf{W}, \tag{4}$$

$$\sum_{j\in\mathbf{V}} S_{cdij}^{2\text{-E}} \le X_c^{\text{CDC}} \qquad \forall c\in\mathbf{L}^{\text{CDC}},\, d\in\mathbf{L}^{\text{DEP}},\, i\in\mathbf{W}, \tag{5}$$

$$\sum_{i\in\mathbf{W}}\sum_{j\in\mathbf{V}}\bigg(\sum_{c\in\mathbf{L}^{\text{CDC}}} S_{cdij}^{2\text{-E}}\bigg)\zeta_j^{\text{space}}\bigg(\sum_{k^{\text{D}}\in\mathbf{K}_i^{\text{D}}}\sum_{k^{\text{P}}\in\mathbf{K}_i^{\text{P}}}\Pr(\Delta_i^{\text{D}}=\hat{\Delta}_{k^{\text{D}}}) \Pr(\Delta_i^{\text{P}}=\hat{\Delta}_{k^{\text{P}}}) q_{dijk^{\text{D}}k^{\text{P}}}^{\text{veh}}\bigg) \le \bar{\zeta}_d X_d^{\text{DEP}} \quad \forall d\in\mathbf{L}^{\text{DEP}}, \tag{6}$$

$$\sum_i\sum_j S_{cij}^{1\text{-E}}\zeta_j^{\text{space}}\bigg(\sum_{k^{\text{D}}\in\mathbf{K}_i^{\text{D}}}\sum_{k^{\text{P}}\in\mathbf{K}_i^{\text{P}}}\Pr(\Delta_i^{\text{D}}=\hat{\Delta}_{k^{\text{D}}}) \Pr(\Delta_i^{\text{P}}=\hat{\Delta}_{k^{\text{P}}}) q_{cijk^{\text{D}}k^{\text{P}}}^{\text{veh}}\bigg) + \zeta_j^{\text{space}}\big|_{j=j^{E2}}\sum_d q_{cd}^{2\text{-E-E2}} \le \bar{\zeta}_c X_c^{\text{CDC}} \qquad \forall c\in\mathbf{L}^{\text{CDC}}, \tag{7}$$

$$X_d^{\text{DEP}}, X_c^{\text{CDC}}, S_{cdij}^{2\text{-E}}, S_{cij}^{1\text{-E}} \in \{0,1\} \quad \forall c\in\mathbf{L}^{\text{CDC}},\, d\in\mathbf{L}^{\text{DEP}},\, i\in\mathbf{W},\, j\in\mathbf{V}, \tag{8}$$

where

$$C_{ijk^{\text{D}}k^{\text{P}}}^{\text{stops}} = \begin{cases} M^{\text{big}} & \text{for } \Delta_i^{\text{D}}+\Delta_i^{\text{P}}=0,\\ C_j^{\text{vol}}(\Delta_i^{\text{D}}+\Delta_i^{\text{P}})^{-1} & \text{otherwise,}\end{cases} \tag{9}$$

$$t_{ij}^{\text{stop-det}} = t_j^{\text{stop}} + t_j^{\text{item}}\rho_i + k^{\text{tour}}\big(\gamma_i^{0.5}s_j^{\text{tour}}\big)^{-1}, \tag{10}$$

$$t_{ijk^{\text{D}}k^{\text{P}}}^{\text{capa}} = C_{ijk^{\text{D}}k^{\text{P}}}^{\text{stops}} t_{ij}^{\text{stop-det}}, \tag{11}$$

$$t_{dij}^{\text{haul}} = k^{\text{haul}} r_{di}\big(s_j^{\text{haul}}\big)^{-1}, \tag{12}$$

$$t_{ijk^{\text{D}}k^{\text{P}}}^{\text{load}} = C_{ijk^{\text{D}}k^{\text{P}}}^{\text{stops}}\rho_i t_j^{\text{item}}, \tag{13}$$

$$n_{dijk^{\text{D}}k^{\text{P}}}^{\text{runs}} = T^{\text{E1}}\big(t_{ijk^{\text{D}}k^{\text{P}}}^{\text{capa}} + t_j^{\text{setup}} + 2t_{dij}^{\text{haul}} + t_{ijk^{\text{D}}k^{\text{P}}}^{\text{load}}\big)^{-1}, \tag{14}$$

$$C_{dijk^{\text{D}}k^{\text{P}}}^{\text{real}} = C_{ijk^{\text{D}}k^{\text{P}}}^{\text{stops}} n_{dijk^{\text{D}}k^{\text{P}}}^{\text{runs}}, \tag{15}$$

$$q_{dijk^{\text{D}}k^{\text{P}}}^{\text{veh}} = A_i\gamma_i\big(C_{dijk^{\text{D}}k^{\text{P}}}^{\text{real}}\big)^{-1}, \tag{16}$$

$$m_{dijk^{\text{D}}k^{\text{P}}}^{\text{tours}} = \max\big(1, n_{dijk^{\text{D}}k^{\text{P}}}^{\text{runs}}\big), \tag{17}$$

$$n_{dijk^{\text{D}}k^{\text{P}}}^{\text{stops}} = \min\big(C_{dijk^{\text{D}}k^{\text{P}}}^{\text{real}}, C_{ijk^{\text{D}}k^{\text{P}}}^{\text{stops}}\big), \tag{18}$$

$$K_{dij}^{2\text{-E-E1}} = \sum_{k^{\text{D}}}\sum_{k^{\text{P}}}\Pr(\Delta_i^{\text{D}}=\hat{\Delta}_{k^{\text{D}}})\Pr(\Delta_i^{\text{P}}=\hat{\Delta}_{k^{\text{P}}}) q_{dijk^{\text{D}}k^{\text{P}}}^{\text{veh}} \cdot \Big(m_{dijk^{\text{D}}k^{\text{P}}}^{\text{tours}}\big(t_j^{\text{setup}}w_j + 2r_{di}\big(s^{\text{haul}}\big)^{-1}\big(w_j+c_j^{\text{veh}}\big)\big) + f_j^{\text{veh}}\Big), \tag{19}$$

$$K_{cij}^{1\text{-E}} = \sum_{k^{\text{D}}}\sum_{k^{\text{P}}}\Pr(\Delta_i^{\text{D}}=\hat{\Delta}_{k^{\text{D}}})\Pr(\Delta_i^{\text{P}}=\hat{\Delta}_{k^{\text{P}}}) q_{cijk^{\text{D}}k^{\text{P}}}^{\text{veh}} \cdot \Big(m_{cijk^{\text{D}}k^{\text{P}}}^{\text{tours}}\big(t_j^{\text{setup}}w_j + 2r_{ci}\big(s^{\text{haul}}\big)^{-1}\big(w_j+c_j^{\text{veh}}\big)\big) + f_j^{\text{veh}}\Big), \tag{20}$$

$$K^{\text{hand}} = c^{\text{hand-DEP}}\sum_c\sum_d\sum_i\sum_j A_i\gamma_i\rho_i S_{cdij}^{2\text{-E}} + c^{\text{hand-CDC}}\sum_i A_i\gamma_i\rho_i, \tag{21}$$

$$K^{\text{fac}} = f^{\text{DEP}}\sum_d X_d^{\text{DEP}} + f^{\text{CDC}}\sum_c X_c^{\text{CDC}}, \tag{22}$$

$$K_{dij}^{\text{space}} = \sum_{k^{\text{D}}}\sum_{k^{\text{P}}}\Pr(\Delta_i^{\text{D}}=\hat{\Delta}_{k^{\text{D}}})\Pr(\Delta_i^{\text{P}}=\hat{\Delta}_{k^{\text{P}}}) \cdot q_{dijk^{\text{D}}k^{\text{P}}}^{\text{veh}}\zeta_j^{\text{space}}c_d^{\text{space}}, \tag{23}$$

$$q_{cd}^{2\text{-E-E2}} = \sum_{k^{\text{D}}}\sum_{k^{\text{P}}}\sum_i\sum_j\Pr(\Delta_i^{\text{D}}=\hat{\Delta}_{k^{\text{D}}})\Pr(\Delta_i^{\text{P}}=\hat{\Delta}_{k^{\text{P}}}) \cdot \big(C_j^{\text{vol}}\big)^{-1}S_{cdij}^{2\text{-E}}A_i\gamma_i\big(\Delta_i^{\text{D}}+\Delta_i^{\text{P}}\big), \tag{24}$$

$$K_{cdj}^{2\text{-E-E2}} = q_{cd}^{2\text{-E-E2}}\big(2k^{\text{tour}}r_{cd}\big(s_j^{\text{haul}}\big)^{-1}\big(w_j+c_j^{\text{veh}}\big) + f^{\text{veh}}\big) + 2t_j^{\text{item}}\big(w_j+c_j^{\text{veh}}\big)\sum_i\sum_{j'}S_{cdij'}^{2\text{-E}}A_i\gamma_i\rho_i. \tag{25}$$

Equation (1) defines the optimization objective, which is to minimize the total daily cost of operation of the currently considered network. Equation (2) ensures that each demand segment is served by exactly one vehicle type within one network. Equations (3) and (5) ensure that indirect shipment to demand segments can only involve active IDs and active CDCs, respectively. Equation (4) ensures that direct shipment to demand segments only involves active CDCs. Equations (6) and (7) enforce capacity restrictions at the ID and the CDC level, respectively. Equation (8) constrains the network type decisions and location decisions to be binary. The variable definitions underlying these constraints are given in Equations (9)–(25). Vehicle-specific, destination-specific carrying capacities are incorporated through the variable C_j^{vol} in Equations (9)–(18). Note that Equation (11) summarizes the continuous approximation approach for interstop travel times and distances developed by Daganzo (2005). The subsequent equations contain the enhancements to the routing cost approximation introduced by Winkenbach et al. (2016).

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