Case Study: JD.com Improves Delivery Networks by a Multiperiod Facility Location Model[1]

1. Introduction

1.1 Motivation

Delivery systems are crucial in various industries like e-commerce, mail services, and food delivery. With the fast-growing demand for delivery services, it is vital to design efficient and adaptive delivery networks. JD.com, China's leading e-commerce company, has a competitive edge in the market due to its advanced logistics system, enabling high-quality delivery services. However, as JD.com expands its market presence and experiences increased demand, it has recognized the need to improve its delivery system to meet customer service targets while reducing operational costs.

1.2 Objective

Historically, JD.com’s delivery station (DS) location plans were made manually by staff in multiple departments from various regions of China. The planning procedure was time-consuming and susceptible to human error. Hence, the objective of this project was to develop a tool capable of automatically generating annual plans for adjusting DS locations on a monthly basis, to minimize total yearly operational costs. For practical use in JD.com, the tool required additional functions, including data preparation and results visualization. Nonetheless, this study mainly focused on the design of optimization models and solution methods.

1.3 Challenges

JD.com faced practical difficulties in implementing the project. Due to its large size, rebuilding the entire delivery network was not feasible. Instead, JD.com sought a gradual transition to a more efficient system while ensuring service quality. This led to various constraints on changing DS locations and coverage. Existing multiperiod facility location models in the supply chain network design literature did not fully address all the practical restrictions faced by JD.com, necessitating the proposal of a new model.

The combination of these constraints and the extensive size of JD.com's delivery networks resulted in a substantial number of variables and constraints in the optimization model. For example, consider Qingdao, a medium-sized city in China, with 545 candidate DS locations and an equal number of demand points. Considering JD.com's 12-period year, an integer programming model with millions of variables and constraints was formulated. For larger cities like Beijing and Shanghai, the model's size becomes even more significant, making it challenging to solve using off-the-shelf solvers or existing methodologies. Consequently, a specialized solution was developed.

1.4 Conclusion

This project developed an optimization model to automatically make annual plans of the delivery stations that minimize operational costs, utilized a mixed-integer linear programming (MILP) method, and proposed techniques to solve the model. The results demonstrate that the proposed model generates improved plans compared with manually planning in terms of both

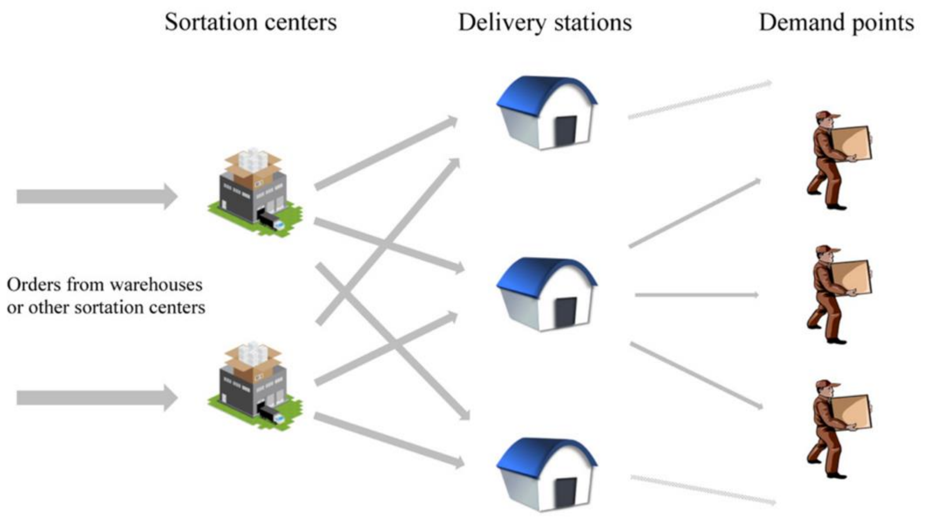
[1] Refer to "Ningxuan Kang, Hao Shen, Ye Xu (2022) JD.com Improves Delivery Networks by a Multiperiod Facility Location Model. INFORMS Journal on Applied Analytics 52(2):133-148." for more details.

operational cost and delivery distance. The tool designed helps JD.com save on delivery costs and gain operational benefits in designing delivery networks.

2. Model for Improving Delivery Networks Basic Settings

A citywide distribution system consists of two logistics infrastructure components (see Figure 1): sortation centers (SCs) and delivery stations (DSs). SCs receive and sort packages before sending them to corresponding DSs. DSs receive packages from SCs and deliver them to end customers. Each DS is assigned to specific blocks within the city, and one delivery person typically serves a single block. The delivery network is modeled as a directed tripartite graph, with SCs, DSs, and blocks as the vertices. Transportation between SCs and DSs, as well as between DSs and blocks, is represented by arcs in the graph. DSs can only be located in blocks, with each block accommodating one DS at most. The model adjusts DS locations and block assignments to create new plans. SC locations are assumed to be fixed due to cost and limited options. The transportation cost between SCs and DSs is negligible compared to the cost between DSs and blocks, which remains relatively stable under different DS locations. DS sites are leased annually and cannot be removed until the lease ends. Existing DSs maintain their size upon renewal, while new DSs select their size within a reasonable range and keep it constant. DS capacity, related to size, determines the maximum number of packages a DS can deliver per month. The fixed cost of setting up a new DS depends on its size, assumed to have a linear relationship with both capacity and cost.

Figure 1. (Color online) A Tripartite Graph Configuration of the Citywide Distribution Network of JD.com



Note. The distribution network of JD.com consists of three layers of vertices, namely, sortation centers (SCs), delivery stations (DSs), and blocks (represented by demand points), as well as transportation arcs between SCs and DSs, and between DSs and blocks.

2.1 Practical Restrictions

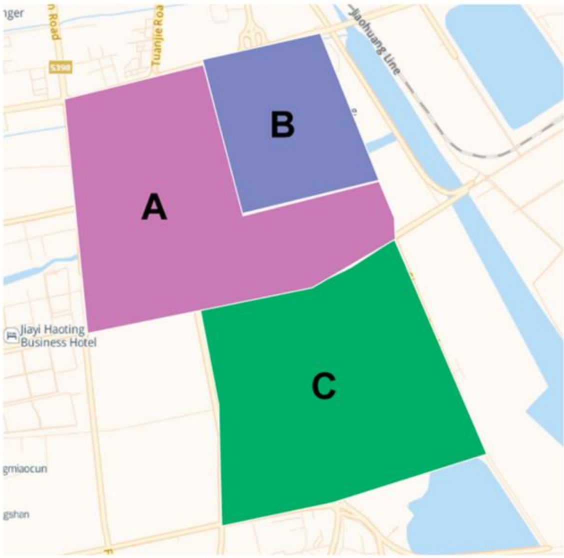
This case incorporated practical restrictions based on JD.com's operational practices into the model to improve the acceptance and launch safety of the DS location plan. These restrictions can be categorized into three groups.

1. DS location changes: This case imposed two types of restrictions. Firstly, set an upper limit on the number of DS location changes per month. This restriction is necessary during peak months like June and November (when the "6.18" and "11.11" sales

promotions take place), and the holiday season in January and February when changes may disrupt service quality or face staffing challenges. Secondly, enforce monotonicity in the total number of DSs over time to avoid fluctuation caused by seasonal shifts in market demand.

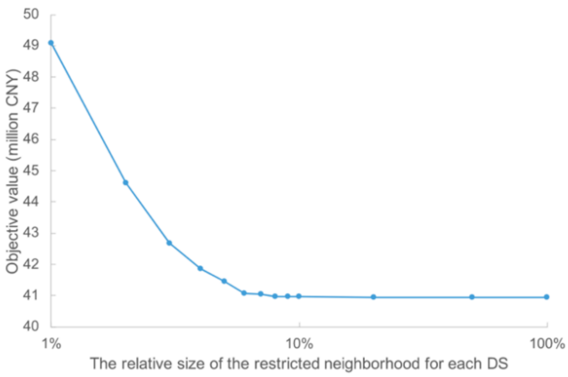
2. Block assignment changes: To minimize frequent reallocation of human resources, this case placed an upper limit on the number of block assignment changes per block during the planning period. Block assignment changes involve reassigning blocks to different DSs, requiring adjustments in personnel organization.

Figure 2. (Color online) Example of Block Adjacency



Notes. This figure illustrates three blocks as an example to explain the concept of block adjacency. In the figure, block A is adjacent to block B and block C, whereas block B and block C are not adjacent.

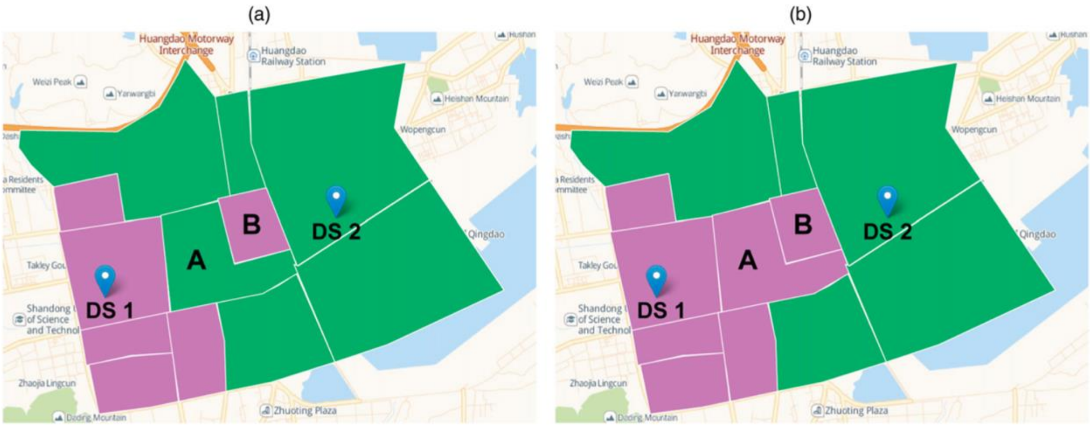
Figure 4. (Color online) Changes to the Objective Value of the Neighborhood-Restricted Problem



Note. This figure illustrates how the objective value (or the total cost) of the neighborhood-restricted problem changes as the relative size of the restricted neighborhood varies in the solution procedure for the Qingdao instance.

3. Connectivity requirement: First, it is important to define "block adjacency" and "connectivity." Two blocks are called "adjacent" if they share at least one side or one vertex. As shown in Figure 2, block A is adjacent to block B and block C, whereas block B and block C are not adjacent to each other. Define a "path" of blocks as a sequence of blocks in which successive pairs of blocks are adjacent. A set of blocks is called "connected" if, for any two blocks in the set, there exists a path between them. Require all blocks assigned to the same DS to be connected in order to benefit from operational flexibility. Figure 3 provides an example to illustrate connectivity and its benefits. There are two DSs in this area, DS 1 and DS 2, and each covers several blocks. In Figure 3(a), the blocks covered by DS 1 are not connected, since block B is not adjacent to any other block covered by DS 1. It is difficult for block B to receive assistance from DS 1 if its delivery man takes sick leave or if there is a surge in the number of packages because the other delivery men from DS 1 have to go across some blocks covered by DS 2 in order to lend a hand. On the contrary, in Figure 3(b), by reassigning block A from DS 2 to DS 1, all blocks covered by DS 1 are connected, so that delivery men in any other block of DS 1 can easily offer assistance to block B.

Figure 3. (Color online) Two Different Plans of Block Assignments for Two Delivery Stations



Notes. The figures illustrate two different plans of block assignments for two delivery stations (DS): DS1 and DS2. In the left figure, the blocks assigned to DS1 are not connected, because block B is not adjacent to any other block covered by DS1. In the right figure, the blocks assigned to each of DS1 and DS2 are connected, which satisfies JD.com's connectivity requirements.

2.2 Parameter Preparations

The model used several types of parameters. The first type, provided by the operation team, included lease durations of DSs, maximum allowable changes in location and assignment, and monthly package delivery numbers per block. Monthly demand was predetermined based on operational objectives. The second type of parameters were estimated using JD.com data, including DS capacity (based on size) and fixed cost (based on location and size), as well as delivery cost (linearly related to distance). The third type of parameters were obtained from external sources, such as delivery distances between DSs and blocks obtained from map service providers, and analysis of block boundaries to identify adjacent blocks and address data issues.

2.3 Formulation

The goal is to generate an annual plan for every city to adjust delivery networks on a monthly basis. This project formulated this problem as a multiperiod facility location model. The objective of the model was to minimize the total cost of the delivery network, which consists of the fixed costs of DSs and the delivery costs from DSs to blocks. The decision variables of the model included the location and the size of each DS, and the monthly assignment of each block to a DS. In addition, this project incorporated some intermediate variables to represent fixed costs, assignment changes, and connectivity. Thus, the decision variables were binary or continuous, and the objective function was formulated as a linear function of the decision variables. In sum, the model considered four groups of constraints: (i) initial conditions, (ii) facility location-allocation constraints, (iii) practical restrictions, and (iv) connectivity requirements[2].

2.4 Solution Approach

As practical experience indicates, blocks are more likely to be designated to a nearby DS rather than a remote one. Hence, this project sought near-optimal solutions by defining the τ%-neighborhood-restricted (τ%-NR) problem, which limited the assignment of each block to DSs within its top τ% nearest blocks. Note that the original (unrestricted) problem was a special

[2] Refer to Appendix for mathematical details.

case of the τ%-NR problem, that is, the 100%-NR problem, where the neighborhood of each DS is the set of all blocks. The parameter τ can be tuned to balance optimality and efficiency of computation.

3. Model Results

The annual planning in Qingdao was used as an example to show the effectiveness of the model.

3.1 Computation Efficiency

Qingdao is a medium-sized city in the east of Shandong Province on the coast of China's Yellow Sea. It contained 51 DSs and 545 blocks at the beginning of 2018. The R^2 of the linear model between the delivery cost per package and the delivery distance for Qingdao in 2018 was 0.909, which suggests that the linear regression model fits the data well. Parameter τ was selected from the set $\{1, 2, \ldots, 10, 20, 50, 100\}$ and the associated nested τ%-NR problems were sequentially solved. Table 1 summarizes the computation performance, and Figure 4 illustrates the objective value in million Chinese yuan (CNY) for each neighborhood-restricted problem. The heuristic gap for a τ%-NR problem in Table 1 is defined as the ratio of the difference between the optimal values of this problem and the unrestricted problem ($\tau = 100$) to the optimal value of the unrestricted problem.

Table 1. Computation Performance Results for the Neighborhood-Based Heuristic with the Nested Warm-Start Algorithm in the JD.com Network in Qingdao

Relative size, τ[a]	Marginal time (seconds)[b]	Accumulative time (seconds)[c]	Heuristic gap (%)
1	34.61	34.61	19.911
2	46.93	81.54	8.985
3	131.25	212.79	4.210
4	8,591.14	8,803.93	2.250
5	28,803.17	37,607.10	1.251
6	1,396.80	39,003.90	0.338
7	1,856.73	40,860.63	0.259
8	6,068.74	46,929.37	0.067
9	1,087.30	48,016.67	0.063
10	1,859.24	49,875.91	0.062
20	10,437.88	60,313.79	0.014
50	9,792.06	70,105.85	0.002
100	18,335.57	88,441.42	0.000

[a]Relative size of restricted DS neighborhood.
[b]The computation time of solving the current problem by using the optimal solution of the former problem as the warm-start solution.
[c]The total computation time of solving the current problem.

The results in Table 1 and Figure 4 show that as τ grows up to 10%, the objective value (or the total cost) reduces significantly within a reasonable computation time frame. However, when the relative size is beyond 10%, a considerable amount of computation effort still has yet to be paid, and little cost improvement is gained. Therefore, solving the 10%-NR problem can substantially save computation time without losing significant optimality.

3.2 Benefits

This work compared the plan generated by the proposed model with the manual plan made by the business team. Table 2 summarizes the costs, DS capacity use rate, and delivery distance of both plans. The model saved 8.08% of the total cost compared with the manual plan. Not surprisingly, most of these cost-savings were due to the reduction in DS fixed costs, as the number of DSs was almost cut in half by the plan. As a result, the average DS use rate had an 11.56 percentage point (pp) increase. This implies that the initial delivery network had surplus DSs. Although the model reduced the number of DSs, it did not increase delivery distance; on the contrary, the average delivery distance was shortened from 5.53 to 5.33 kilometers (km) (–3.61%), which significantly improved customer experience.

To better benchmark the model results, this work also ran a model without initial conditions, namely, the initial DS locations and the initial block-DS assignments, for Qingdao in 2018. Such a benchmark model selected the best DS locations and block assignments from the first month without considering existing DSs and thus provided a theoretical lower bound on the total cost. This bound, although it cannot be reached in practice, indicates the maximum potential for cost savings. A comparison of the model plan with the benchmark plan was given in the last two columns of Table 2. The model resulted in improvements equal to nearly 50% of its potential (8.08%, with a possible 16.45% reduction in total cost) and recommended a DS number very close to that in the benchmark plan (29 vs. 28).

Table 2. Plan Comparison for Qingdao in 2018

	Manual plan	Model plan (% change)	Benchmark plan (% change)
Total cost (CNY)	44,567,733	40,967,948 (–8.08%)	37,235,276 (–16.45%)
Fixed cost (CNY)	14,270,108	10,927,427 (–23.42%)	7,333,800 (–48.61%)
Delivery cost (CNY)	30,297,625	30,040,521 (–0.85%)	29,901,476 (–1.31%)
DS number in the last month	54	29 (–46.30%)	28 (–48.15%)
DS capacity use rate	37.14%	48.70% (11.56 pp)	74.18% (37.04 pp)
Average delivery distance (km)	5.53	5.33 (–3.61%)	5.22 (–5.58%)

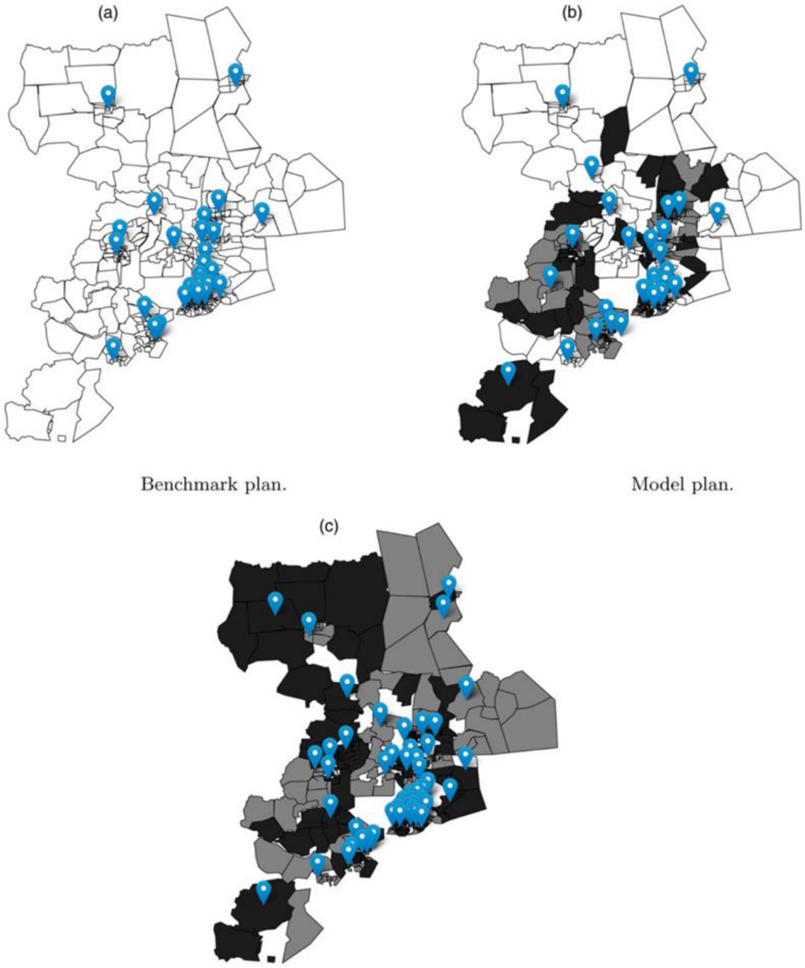
Figure 5 illustrates the DS locations in Qingdao at the end of the planning horizon (December 2018) recommended by the benchmark plan, the model plan, and the original manual plan. The blue pins denote DS locations, whereas the white, gray, and black blocks in Figure 5, (b) and (c), can be interpreted as follows: Compared with the benchmark plan in Figure 5(a), white blocks are covered by the same DS without location change, gray blocks are covered by the same DS that is moved to another block nearby, and black blocks are covered by a new DS. The maps illustrate that the model plan is more similar to the benchmark plan than it is to the manual plan, with regard to the network configuration. Nonetheless, the benchmark plan suggests 26 DS changes at once in January, whereas the model recommends an easier-to-implement plan by distributing 17 DS changes to seven months, each of which is assigned up to seven DS changes.

4. Implementation

The model was embedded in a new DS location planning tool designed for the annual planning of JD.com's delivery system. This project contributed to the tool by developing its core optimization program, including the DS location model and the solution algorithm, and by designing both the architecture and the visual interface of the tool. In addition, the research team also helped the engineering team with the software coding and testing processes. The following briefly introduces the main functions of the tool.

To generate a plan for a city, the DS location planning tool first extracts historical operational and geographical data from JD.com's Big Data Platform and generates input data for the model. The optimization program then builds the optimization model with input data and solves for the optimal solution for each city. After the solution procedure is complete, the tool converts the solution into a plan and displays it on a visual interface, as shown in Figure 6.

Figure 5. (Color online) Comparison of the DS Locations and Block Assignments



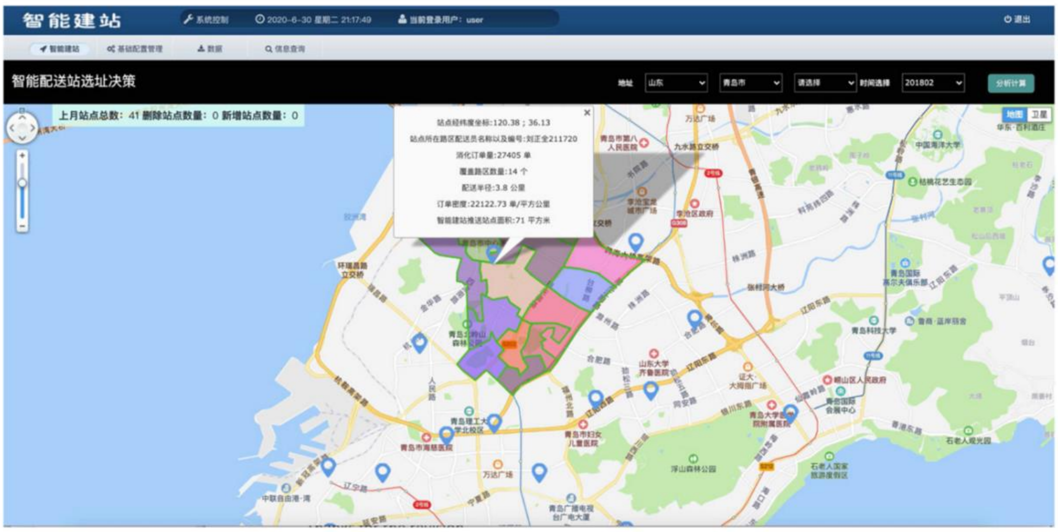
Benchmark plan.

Model plan.

Manual plan.

Notes. The figures show a comparison of the DS locations and the block assignments of the benchmark plan (a), our model plan (b), and JD.com's previous manual plan (c) for Qingdao in 2018. The blue pins denote DS locations; the white, gray, and black blocks in the middle and right figures can be interpreted as follows: compared with the left figure, white blocks are covered by the same DS without location change, gray blocks are covered by the same DS, which is moved to another block nearby, and black blocks are covered by a new DS.

Figure 6. (Color online) Visual Interface of JD.com's DS Location Planning Tool



Notes. The screenshot shows the visual interface of JD.com's DS Location Planning Tool. The screenshot displays the (colored) blocks assigned to a delivery station in our model plan for Qingdao in February 2018.

In the visual interface, all of the DS locations and blocks are shown on a map, and blocks covered by the same DS have the same color. Once the user clicks on a DS mark, its basic information pops up and the blocks covered by that DS are highlighted on the map (Figure 6). Users can conveniently query DS locations and block assignments through this visual interface. The map view also enables a comparison of the model plan and the benchmark plan (discussed in the Benefits section). Furthermore, the research team designed a module to export the plan into spreadsheets, making it easier for the operation team to share, analyze, and modify the results.

JD.com selected 16 major cities, covering more than 650 million packages in China, as pilot cities for this project. The operation team in charge of these pilot cities can download and use the recommended plan to guide the practical design of their delivery networks, including opening, closing, and relocating DSs. The prototype of the DS location planning tool has been endorsed by the operation team of JD Logistics.

4.1 Impact

This project generated 2018 annual delivery network plans for the 16 pilot cities with the help of the model described in this paper. The results show that the plans generated by the model have great economic impacts. Compared with manual plans, it was estimated that the plans could save over 82 million yuan in DS deployment and delivery services, 4.2% of the total cost of DS networks in 2018.

Moreover, this project also demonstrated noneconomic impacts. First, the plans outperformed the manual plans in terms of customer experience. The models showed that the average delivery distance per package from DSs to customers could be reduced by 20.9%, from 3.83 to 3.03 km. This reduction would then significantly improve the timeliness of delivery and thus customer experience as well as network efficiency. Second, the DS Location Planning Tool increased the employee efficiency of JD.com. Traditionally, plans were made manually by staff from many departments, and it usually took at least a month to manually make an annual plan for a medium-sized city; for larger cities, the planning process was even more time-consuming. By contrast, the model, embedded in the DS location planning tool, provides an automatic mechanism for the company to make DS location plans only within hours. Last but not least, this project, which successfully applied operations research techniques, has been recognized throughout the company and has made other departments interested in the critical value of automated and optimized decision support.

5. Lessons Learned, Challenges, and Future Plans

The research team devoted great efforts to persuading the operation team at JD.com to accept and use the DS location planning tool for their annual plans for delivery networks. At the beginning of the project, the research team spent huge amounts of time communicating with potential users of the tool from diverse departments in the corporation and understanding their needs, requirements, and expectations. Throughout this project, the research team constantly received feedback from the operation team and accordingly modified the model. Several times, constraints were added in response to the new practical restrictions, and these restraints fundamentally complicated the model, disabled the original solution methods, and motivated us to develop different solutions. After finishing the prototype of the DS location planning tool, the research team collected numerous manual plans of different cities, as well as associated data, and conducted extensive numerical experiments to demonstrate the effectiveness and efficiency of the model. They also incorporated several extended and optional functions in the tool to tackle different practical restrictions that may arise in the future.

Nonetheless, several practical challenges complicated the implementation of the recommended plan. One principal challenge was that appropriate housing resources were not always available in designated blocks. An appropriate location for a DS should be (i) ground level with an independent entrance and a sufficiently large parking space and (ii) in a neighborhood without heavy traffic. In addition, the rental price in certain blocks could be much higher than expected. Recognizing this challenge, the research team planned to continue the research to optimize implementation. First, they planned to add access to detailed and real-time information on housing resources, including prices, locations, sizes, and so on, from third-party platforms to the DS location planning tool. Meanwhile, they would incorporate this information into the decision model and enable the tool to recommend not only good blocks for particular DSs but also the appropriate housing resources within each block. Second, they planned to collect historical traffic data and extend the tool by providing traffic heat maps to help the operation team efficiently select suitable neighborhoods as DS locations.

Another challenge was the difficulty in updating the recommended plan responsively as a demand surge or inconsistency between the implementation and the recommendation was observed or expected. Originally, to cope with demand or implementation uncertainties, the DS planning tool was designed for use at any time point for any planning horizon, as long as data were available. However, frequently and responsively updating the recommended plan is difficult in practice for two reasons. First, frequent plan changes can impair service quality and are difficult to implement, because of, for example, the housing resource issue. Second, in the practice of JD.com, it takes over a month to enter a leasing/renewal decision into the system, because it is a manual process done on an ad hoc basis. Given the long feedback loop of offline operations, it is almost impossible to run the planning tool with an accurate new initial condition and update the plan responsively. These issues, enclosed in the feedback that the research team received from the operation team in the first quarter of 2018, led to a partial implementation of the recommended annual plans in 2018. For example, the realized annual demand of Qingdao in 2018 was observed to be 40% higher than expected due to a significant increase in third-party waybills and an aggressive expansion of the fresh food market. As a consequence, the actual network at the end of 2018 deviated from the model plan; some DSs that the model plan recommended to be closed were kept open, and a few new DSs were set up at unplanned areas, resulting in higher operational costs.

To overcome this challenge and to shorten the offline feedback loop, the research team had been working with JD.com's business and engineering teams to build a standard data collection procedure and an easier-to-use interface for the data collection system. In addition, to strengthen the adaptability of the DS Location Planning Tool, the research team planned to extend it to allow for manual changes and provide what-if analyses for different situations.

Despite the challenges, the results generated by the model instructed the operation team to design new yearly plans. For example, compared with the original manual plan, the model results advised fewer stations in remote regions, so the operation team then removed redundant stations in these areas. Another optimization step was the timing of opening new DSs. The manual plans tended to open new DSs at the beginning of a year. The model results recommended that new DSs were opened according to package quantity of each month. These suggestions were all adopted by the operation team in the delivery system design for pilot cities in 2018.

6. Summary

After experiencing several market expansions, JD.com faced logistical challenges; its system must be revised. More specifically, quick-shifting demand, redundant infrastructure, and market competition heavily burdened its logistics system. The manual adjustments of the delivery network JD.com had traditionally used were inefficient and costly. Accordingly, this project leveraged the research team's expertise in operations research to formulate the planning problem as a multiperiod facility location model and developed an automatic location planning tool to improve JD.com's delivery networks. The model minimizes the total cost of the network and accounts for a variety of practical constraints. More specifically, this project developed an efficient neighborhood-based approximation model and incorporated a warm-start mechanism to accelerate the solution. Numerical tests verified the model's effectiveness. Compared with JD.com's manual plans, the model generated more efficient networks with shorter delivery distances, higher DS use rates, and lower operational costs. This work embedded the model into an automatic planning tool that enables JD.com to efficiently generate an optimal plan for every city in China.

This work follows the "customer first" principle, one of the core values of JD.com. An efficient delivery network makes it possible for customers to pay less and enjoy better services at the same time. On the one hand, shorter delivery distances enable the company to provide faster and more reliable delivery. On the other hand, lower operational costs enable the company to offer lower prices to customers in the long term. In the future, JD.com would extend its implementation of this tool to all cities to achieve greater savings and bring even more value to customers.

Appendix. Mathematical Model

This section presents the notation of the original model, as well as its mathematical details. This project applied a mixed linear integer programming (MILP) method to generate the yearly plan of delivery station locations. The following is a summary of the notation.

Indices

$j \in J$: index of either a block or a delivery station located at this block; J is the block set

$j \in \hat{J}$: index of a block without a delivery station, $\hat{J} \subseteq J$

$j \in \bar{J}$: index of a block that cannot be selected for DS, $\bar{J} \subseteq J$

$t \in T$: index of a period; $T = \{1,2, \dots ,12\}$ for a yearly plan

Parameters

d_{jk} : distance in kilometers between block j and block k, $j, k \in J$

α_d : constant term in unit delivery cost function of packages (in Chinese renminbi [RMB])

β_d : coefficient of delivery distance in unit delivery cost function of packages (in CNY/km)

n : limits on the number of assignment changes for each block over a year

n_t : limits on the number of location changes of all delivery stations during month t; a location change includes adding a new station or relocating an old station, $t \in T$

n_t^c : limits on the number of assignment changes for all blocks during month $t, t \in T$

t^{start} : the first month when adjustments are allowed, $t^{\text{start}} = \min\{t \in T \mid n_t > 1\}$
m_j : the last month of the lease of DS $j, j \in J \setminus \hat{J}$
y_{0jk} : initial assignment, $j, k \in J$; $y_{0jk} = 1$ if block k is initially assigned to station j; $y_{0jk} = 0$ otherwise
q_{tj} : number of packages to be delivered to block j at month $t, t \in T, j \in J$
α^{cap} : constant term of station capacity-DS size function
β^{cap} : coefficient of DS size in station capacity-DS size function
α^{cst} : constant term of the station cost
β_j^{cst} : unit DS size cost of block j (in RMB / month $/m^2$), $j \in J$
s_{0j} : initial DS size of block j; if there is no initial DS at block $j, s_{0j} = 0, j \in J$

s^{lb}, s^{ub} : lower bound and upper bound of size of new DSs
a_{jk} : connectivity indicator; $a_{jk} = 1$ if block j and k are adjacent, $a_{jk} = 0$ otherwise, $j \in J$

Decision Variables

$$X_{tj} = \begin{cases} 1 & \text{if a DS exists at block } j \text{ in period } t, \\ 0 & \text{otherwise,} \end{cases} \quad t \in T \cup \{0\}, j \in J$$

$$Y_{tjk} = \begin{cases} 1 & \text{if block } k \text{ is assigned to DS } j \text{ in period } t, \\ 0 & \text{otherwise,} \end{cases} \quad t \in T \cup \{0\}, j, k \in J$$

$$W_{tk} = \begin{cases} 1 & \text{if the station to which block } k \text{ is assigned changes in period } t, \\ 0 & \text{otherwise,} \end{cases} \quad t \in T, k \in J$$

$S_{tj} \geq 0$: DS size of block j in month t, $t \in T \cup \{0\}, j \in J$
$Z_{tj} \geq 0$: DS cost of block j in month t, $t \in T \cup \{0\}, j \in J$
$F_{kl}^{tji} \geq 0$: flow originating from block j, passing through block k and l, which are adjacent (i.e., $a_{kl} = 1$), and terminated in block i in month t, $t \in T, i, j, k, l \in J, a_{kl} = 1$

Objective Function and Constraints

The objective (A.1) of the model is to minimize the yearly total cost, which consists of the total fixed cost of DSs and the total delivery cost from DSs to blocks. Constraints (A.2) and (A.4) initialize the locations and size of the DSs. Constraints (A.5) forbid any DSs built on blocks that cannot be selected for DS. Constraints (A.6) and (A.7) ensure that each initial delivery station cannot be cancelled or change size within its lease duration. Constraints (A.8) - (A.15) guarantee that (i) each station stays open until the end of the year once it is newly opened or re-rented; (ii) once an existing DS is removed, no DS can be located on its block until the end of the year; (iii) the limits are satisfied on the number of location changes of all DSs at each period; and (iv) the size of a newly opened DS is limited within the given range. Constraint (A.16) requires that the number of DSs does not increase during the year because Qingdao has surplus DSs at the beginning and the monotonicity requirement. Constraint (A.17) initializes the assignments of blocks to DSs. Constraint (A.18) requires that each block be assigned to only one DS. Constraints (A.19) and (A.20) guarantee that a DS must cover at least one block and that the capacity of each station cannot be violated. Constraints (A.21) - (A.23) ensure that the restrictions on assignment changes are satisfied. Constraints (A.24) - (A.29) ensure the connectivity among blocks covered by the same DS. Constraint (A.30) defines the fixed cost of DSs. Constraints (A.31) - (A.36) define the variables.

$$
\begin{aligned}
(\mathbf{P}):\quad \min\quad & \textstyle\sum_{t\in T}\sum_{j\in J} Z_{tj} + \sum_{t\in T}\sum_{j\in J}\sum_{k\in J} q_{tk}\left(\alpha_d + \beta_d d_{jk}\right) Y_{tjk} && (A.1)\\
\text{s.t.}\quad & X_{0j} = 1\ \forall j \in J \setminus \hat{J} && (A.2)\\
& X_{0j} = 0\ \forall j \in \hat{J} && (A.3)\\
& S_{0j} = s_{0j}\ \forall j \in J && (A.4)\\
& X_{tj} = 0\ \forall t \in T, \forall j \in \bar{J} && (A.5)\\
& X_{tj} = 1\ \forall j \in J \setminus \hat{J}, \forall t \in \{1,2,\dots,m_j\} && (A.6)\\
& S_{tj} = s_{0j}\ \forall j \in J \setminus \hat{J}, \forall t \in \{1,2,\dots,m_j\} && (A.7)\\
& X_{t,j} = X_{t-1,j}\ \forall j \in J \setminus \hat{J}, \forall t > m_j + 1 && (A.8)\\
& S_{t,j} = s_{0j} X_{tj}\ \forall j \in J \setminus \hat{J}, \forall t \geq m_j + 1 && (A.9)\\
& X_{t-1,j} \leq X_{tj}\ \forall j \in \hat{J}, \forall t \in T && (A.10)\\
& S_{tj} \leq S_{t-1,j} + s^{ub}\left(1 - X_{t-1,j}\right)\ \forall j \in \hat{J}, \forall t \in T && (A.11)\\
& S_{t-1,j} \leq S_{tj}\ \forall j \in \hat{J}, \forall t \in T && (A.12)\\
& S_{tj} \leq s^{ub} X_{tj}\ \forall j \in \hat{J},\ \forall t \in T && (A.13)\\
& S_{tj} \geq s^{lb} X_{tj}\ \forall j \in \hat{J}, \forall t \in T && (A.14)\\
& \textstyle\sum_{j\in\hat{J}} X_{tj} - \sum_{j\in\hat{J}} X_{t-1,j} \leq n_t\ \forall t \in T && (A.15)\\
& \textstyle\sum_{j\in J} X_{t-1,j} \geq \sum_{j\in J} X_{tj}\ \forall t \in T && (A.16)\\
& Y_{0jk} = y_{0jk}\ \forall j,k \in J && (A.17)\\
& \textstyle\sum_{j\in J} Y_{tjk} = 1\ \forall t \in T, \forall k \in J && (A.18)\\
& \textstyle\sum_{k\in J} Y_{tjk} \geq X_{tj}\ \forall t \in T, \forall j \in J && (A.19)\\
& \textstyle\sum_{k\in J} q_{tk} Y_{tjk} \leq \alpha^{cap} X_{tj} + \beta^{cap} S_{tj} && (A.20)\\
& \forall t \in \{t^{\text{start}},\dots,12\}, \forall j \in J && \\
& Y_{tjk} - Y_{t-1,jk} \leq W_{tk}\ \forall t \in T, \forall j,k \in J && (A.21)\\
& \textstyle\sum_{k\in J} W_{tk} \leq n_t^c\ \forall t \in T && (A.22)\\
& \textstyle\sum_{t\in T} W_{tk} \leq n\ \forall k \in J && (A.23)\\
& \textstyle\sum_{l\in J: a_{lk}=1} F_{lk}^{tji} - \sum_{l\in J, a_{kl}=1} F_{kl}^{tji} = 0 && (A.24)\\
& \forall t \in T, \forall i,j,k \in J: j \neq i, j \neq k, i \neq k && \\
& \textstyle\sum_{l\in J: a_{lk}=1} F_{lk}^{tji} - \sum_{l\in J, a_{kl}=1} F_{kl}^{tji} = -Y_{tjk}\ \forall t \in T, && (A.25)\\
& \forall i,j,k \in J: j \neq i, j = k && \\
& \textstyle\sum_{l\in \in: a_{lk}=1} F_{lk}^{tji} - \sum_{l\in J, a_{kl}=1} F_{kl}^{tji} = Y_{tjk} && (A.26)\\
& \forall t \in T, \forall i,j,k \in J: j \neq i, i = k && \\
& F_{kl}^{tji} \leq Y_{tji}\ \forall t \in T, \forall i,j,k \in J: j \neq i, a_{kl} = 1 && (A.27)\\
& F_{kl}^{tji} \leq Y_{tjk}\ \forall t \in T, \forall i,j,k \in J: j \neq i, a_{kl} = 1 && (A.28)\\
& F_{kl}^{tji} \leq Y_{tjl}\ \forall t \in T, \forall i,j,k \in J: j \neq i, a_{kl} = 1 && (A.29)\\
& Z_{tj} \geq \alpha^{cst} + \beta_j^{cst} S_{tj} - \left(\alpha^{cst} + \beta_j^{cst} s^{ub}\right)\left(1 - X_{tj}\right) && (A.30)\\
& \forall t \in T, \forall j \in J && \\
& X_{tj} \in \{0,1\}\ \forall t \in T \cup \{0\}, \forall j \in J && (A.31)\\
& Y_{tjk} \in \{0,1\}\ \forall t \in T \cup \{0\}, \forall j,k \in J && (A.32)\\
& W_{tj} \in \{0,1\}\ \forall t \in T, \forall j \in J && (A.33)\\
& S_{tj} \geq 0\ \forall t \in T \cup \{0\}, \forall j \in J && (A.34)\\
& Z_{tj} \geq 0\ \forall t \in T, \forall j \in J && (A.35)\\
& F_{kl}^{tji} \geq 0\ \forall t \in T, \forall i,j,k,l \in J: a_{kl} = 1 && (A.36)
\end{aligned}
$$