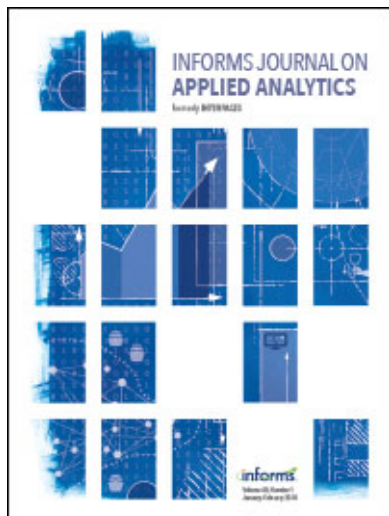




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CPEL Redesigns Its Land Express Network

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The China Postal Express and Logistics Corporation (CPEL), China's largest corporation in the express delivery industry, is restructuring its nationwide land express network after completing its reorganization. In this redesign project, we proposed a network design framework and developed a decision support system (MMHH-SNDDSS) to integrate and optimize the topology structure and functional configuration of CPEL's intermodal and multilayered network. Our model seeks to minimize operations and investment costs, constrained by the delivery time limits of CPEL's service products. Using MMHHSNDDSS, CPEL's senior management team can determine the optimal network by incorporating soft constraints, such as the experience of CPEL's decision makers, into a series of solutions. According to an evaluation based on data gathered in 2009, CPEL expects the new network to improve service levels and provide savings of more than 20 percent in annual operations costs. The implementation of our proposed solution began in 2010. In addition, the quantitative methods applied in this project have changed the company's attitude toward applying operations research methods to strategic decision-making processes.

Key words: industries; transportation and shipping; technology; models; network.

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As an emerging market, China's domestic express industry has developed rapidly in the past decade. From 2004 to 2012, the average demand increased by over 30 percent.

The China Postal Express and Logistics Corporation (CPEL), focuses on operating postal express and logistics products, including well-known brands such as Express Mail Service (EMS) and China Post Logistics (CNPL). In March 2008, the China Postal Group (CPG) began to merge and reorganize the EMS and CNPL companies into a new company. In July 2010, the new company, CPEL, was officially founded. CPEL must deliver an average of 3 million express items each day to more than 200 countries and 2,800

domestic counties and cities. With annual revenue of \$2.7 billion and 10,000 employees, CPEL is the largest express company in China, and is the only company with a network that covers all of China.

CPEL's services include various products with significant differences in delivery speeds, such as same-day, intracity, delivery, next-morning, next-day, second-day, economical delivery, and China postal express freight. Within any region of its network, CPEL provides timely services of all the aforementioned products via land express transportation. For express services involving more than one region, CPEL has built its all-night-flight air network, which consists of an aircraft fleet of 14 planes, 14 key nodes,

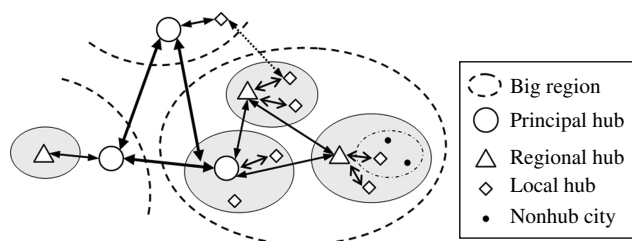


Figure 1: CPEL's former network is a multilayered hybrid hub-and-spoke network with point-to-point links between hub nodes in different regions.

and 40 specialized airline routes, with Nanjing as its center. In addition, 1,759 first-class postal lines are routed through rented civil aircraft.

The former CPEL network comprised three layers, the local hub (LH), the regional hub (RH), and the principal hub (PH) (see Figure 1). Trucks collected and carried express items from any origin city to its LH, which was used previously as a sorting center for the National Universal Postal Network (NUPN). At the LH, items were sorted, sealed into postal bags, and assigned to destinations. Destinations of postal bags were classified into three types: (1) type 1—the destination is within the same region (the grey solid line ellipse in Figure 1) as the origin's LH; (2) type 2—the destination is in a different region within the same big region (BR, the largest dotted line ellipse in Figure 1); and (3) type 3—the destination is in a different BR. After they were carried to the corresponding RH by trucks, type 1 postal bags were transferred to their destination LH by trucks. Type 2 postal bags were transferred to the RH of their destination region and then to their LH by trucks, and the short time-limited products between RHs, such as next-morning delivery, next-day delivery, and second-day delivery, were transferred by air. Type 3 postal bags were transferred to the corresponding RH by aircraft (mainly for next-morning delivery, next-day delivery, or second-day delivery) or to the corresponding PH by trains (for the others), and thereafter to the corresponding RH and (or) LH by truck. In addition, if the shipment volume between an origin city (or LH, RH, and PH) and a destination city was sufficiently large, a direct shipment mode was considered.

Prior to implementing CPEL's new organization, both EMS and CNPL operated on NUPN, a CPG-owned network. As part of the reorganization,

an independent express service network had to be separated from NUPN and restructured. In July 2008, CPG launched the current project to redesign the land express network for CPEL. The aim of this project was to define the network's physical structure, including the hub locations and the spatial layout of the land network. Quantitative methods were required to evaluate the economic performance of the network, while considering delivery time restrictions of various products. In addition to hard constraints, we included some soft restrictions, such as the perceptions of decision makers, an important factor when designing such a large-scale network.

After two years of effort, including two field investigations in the relevant business sectors throughout China, more than 30 seminars with CPEL, a series of discussions and analyses on the draft proposals of the redesign, mathematical modeling, building algorithms, and developing decision support systems, we provided a solution for the redesign of CPEL's land express network that relies strongly on an operations research (OR) approach. After evaluating our proposed network solution, CPEL concluded that it would achieve savings of 20 percent in operations costs and lay a solid foundation for addressing the fierce competition it anticipated in the express market.

Challenges in Redesigning CPEL's Land Express Network

As we describe earlier, the hub-and-spoke network is the basis of CPEL's land express network. The existing methods for addressing the classic network design problem (O'Kelly 1987, Alumur and Kara 2008) are powerful. However, CPEL's network has distinct characteristics that make redesigning it challenging.

Characteristics of CPEL's Land Express Network

In designing a classic hub-and-spoke network, the basic challenges include the location of hubs and the allocation of nonhub nodes to hubs. However, the CPEL network has the following distinct characteristics.

(1) Products in the network are limited by time.

In any express company, including CPEL, the primary service objective is to safely and punctually deliver items to the required destinations within the promised time limits.

(2) Express items should be sorted in the network.

In contrast to the classic transportation network, in which items are assumed to be homogeneous, each item in an express network has a specific origin and destination, making these items heterogeneous. Therefore, during the delivery process, in addition to being transported and transferred between nodes, items must be picked up, sorted, and sealed. It suggests that the configuration of these functions (i.e., allocation of transport, transfer, pickup, sorting, sealing) could be flexible. This can have a significant impact on the delivery time. Using the EMS standard product as an example, we found that the sorting processes accounted for about 30 percent of the total delivery time in the former EMS network. This suggested to us that using centralized sorting (i.e., sorting in only a limited number of selected hubs) could substantially reduce the total delivery time and significantly improve operations. However, the location of the sorting function (i.e., in which layer of the network and in which hubs) required additional decision variables in our network design.

(3) CPEL's network is intermodal and multilayered.

In addition to the aforementioned characteristics of general express networks, CPEL's network is intermodal and has multiple layers. In particular, air and land networks overlap at the regional level.

In this intermodal network, all CPEL products must be handled by the land network within a region (see Figure 1). However, because of the time limits, when a product needs to be transported across regional boundaries, an air network is used for next-morning, next-day, and second-day deliveries, and land networks are used for other products. Therefore, air and land networks overlap (see Figure 2).

Because of restrictions on CPEL's investment budget, we could not change the air network in this project. Nevertheless, in redesigning the land network, we needed to consider specific constraints that the air network imposed. For example, within a region, the land network had to support all the products, including next-morning, next-day, and second-day deliveries; in addition, in selecting hubs in the land network, we had to consider the boarding and landing locations in transporting cross-region products using the air network.

(4) Distribution of cities of the express service demand is unbalanced among cities.

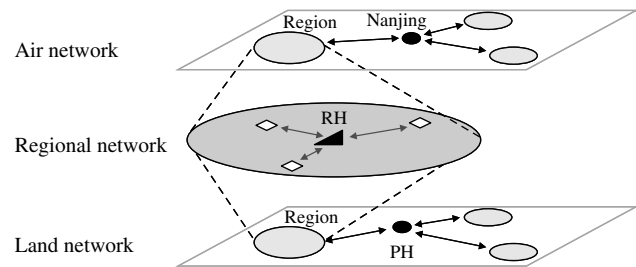


Figure 2: In this example, the air network is used for next-day and second-day delivery across regions; the land network can also be used for other services across regions. However, in any region, the network must support all services. That is, air and land networks overlap at the regional level.

CPEL is a CPG member and a state-owned company; therefore, its objectives include both reducing costs and being socially responsible. The latter objective distinguishes CPEL from other express companies, and requires that its network must cover all cities in the country. This increases the scale of its network and complicates its network design and operation.

In the past decades, China's economic development in its provinces has been uneven. Consequently, the express business market has grown mainly in developed areas, such as the Yangtze River Delta, the Pearl River Delta, and the Bohai Rim, which generate more than 70 percent of CPEL's business.

This uneven distribution of express business across China caused us to ask these questions: Should all areas maintain the same network structures, or should some areas have a separate network structure for dealing with larger volumes of demand? In the areas with low express business demand, but long distances between cities (e.g., northwestern China), should we define networks using similar distance constraints? In summary, the process of redesigning CPEL's network had to reflect the local needs, conditions, and developing trends in China.

The Challenges

Because of the aforementioned characteristics, we faced three challenges in our network redesign project:

(1) Design of the physical structure of the network.

The former CPEL network was a three-layer hybrid hub-and-spoke network. The first questions we had to resolve were whether or not this layer configuration was reasonable, why it was reasonable (or unreasonable), and which type of physical structure could improve the network performance.

(2) Coordination of physical structure and function configuration.

A traditional network design often disregards the function configuration; thus, it considers all optional hubs as homogeneous. However, because CPEL's network is multilayered and its deliveries have time limits, the functions of storage, sorting, sealing, and exchange must be assigned appropriately to different layers and nodes (hubs) to shorten delivery times. Therefore, our redesign project had to integrate structural design and functional configuration. In particular, because machines are expensive investments and can substantially affect (i.e., reduce) the total delivery time, we had to appropriately allocate the function of large-scale automatic sorting. This complicated our network redesign.

(3) Consideration of decision-maker experiences.

The experiences of decision makers are of significant value in designing a strategic network of this kind. We frequently observed this during our work. We could not quantify some factors, such as a city's competitive power, transportation accessibility, or support from local government, in our decision models. However, because these soft constraints would strongly influence the final plan, we had to consider them, which resulted in challenges in incorporating them into our optimization models.

The Planning Methodology and Achievements

In this section, we define the key problems we encountered in redesigning the network, based on the characteristics and challenges we mention earlier. We also provide our framework for solving these problems, technical details of our modeling, and a brief introduction to the decision support system (DSS) we developed.

Redesigning the CPEL Express Network: Key Problems

In discussions with CPEL, we confirmed that we needed to address the following issues when redesigning its land express network:

- Number of layers in the network
- Function of each layer
- Products supported by each layer

• Basic structure of each layer, which we defined as follows:

- Types of topological structures that could be used (broken-line, star-shaped, or fully connected)
- Which nodes (cities) could be selected as hubs
- Coverage of nodes (cities) by each hub
- Flexibility of the network design (primarily the decision on whether or not to implement a direct route)

When the volume between two nodes is sufficiently large, a direct route should be an option. However, we still had to investigate when and where we could establish such routes.

We proposed the following steps for redesigning the network:

- (1) Collect and organize data
- (2) Forecast demand and analyze key markets and cities
- (3) Propose the overall redesign framework
- (4) Formulate models
- (5) Develop a DSS
- (6) Analyze results
- (7) Present strategic recommendations

Our network redesign was basically an optimization problem. Our objective was to minimize the construction and operations costs, while satisfying service-level requirements (i.e., limits on delivery times). Several researchers have analyzed similar problems (Current et al. 1986, Leung et al. 1990, Zäpfel and Wasner 2002, Tang et al. 2008, Teypaz et al. 2010). Researchers have applied network design and optimization techniques to intracity express networks (Kuby and Gray 1993, Cheung et al. 2001, Lin 2010), air networks for express companies (Barnhart and Schneur 1996, Armacost et al. 2004), highway transportation for postal services (Pajunas et al. 2007), freight railway systems (Jeong et al. 2007), and natural gas transmission networks (Kabiriana and Hemmatib 2007). These research efforts have focused primarily on tactical issues, such as analysis of traffic distribution, general empty balancing, and vehicle and crew planning (Wieberneit 2008). The physical structures of these networks are usually considered to be of the hub-and-spoke type or are configured as hierarchical structures. However, the complexity of CPEL's network lies in its characteristics—it is a multiproduct, multilayered hybrid hub-and-spoke network with definite time limits, and its service function must be

coordinated with its physical structure. We know of no published work that addresses an express network within a similar design context.

Planning Framework

To resolve these key problems, we created a planning framework (see Figure 3).

First, we considered the number of layers that would be appropriate. CPEL's former land network had three layers, which suggested to us that a three-layered structure might be appropriate for our purposes. Nevertheless, we experimented with higher and lower numbers of layers to investigate the impact on network performance. Considering the time-limit requirements for different express products and the convenience of scheduling and controlling operations, we developed three cases in which we set the layer number to $n = 2, 3$, and 4. Our objective was to compare the results of these cases to determine the most appropriate (i.e., optimal) number.

Second, having chosen the number of layers, our next decision concerned allocating the sorting function to layers (i.e., investing in large-scale automatic sorting machines). We enumerated each allocation plan and compared the corresponding optimal solutions in each plan to determine the most optimal plan and the corresponding optimal sorting function configuration.

In the process of enumerating these allocation plans, having allocated the sorting function, we needed to find the products supported by the first layer (the top layer), which connects BRs in the network, and determine the longest time limit for these products. Then the core module of the network design emerges, as represented by the shadowed rectangle (Network designing) in Figure 3. Using the longest time limit of all products, we designed the first layer by dividing the country into BRs, locating the corresponding PHs, and allocating cities to each PH. In this framework, the PHs are designed to distribute express products within BRs and interchange products between BRs. Our objective was to pursue economies of scale in transportation costs and investment.

Our next step was to determine whether we should further subdivide these BRs. The answer depended on the following issues:

- Could we satisfy the time limits of all products in each respective BR?

- Would a substantial detour emerge in any BR?
- Would the single-hub network structure match the levels of economic development of the developed BRs?

In particular, business between cities in developed areas was likely to reach the threshold value for opening a direct route in the near future. Therefore, we investigated whether implementing a multihub hub-and-spoke network (involving a subdivision of the BRs) would be less expensive than a single-hub hub-and-spoke network within each BR.

In summary, based on the time-limit criterion and on economic targets, we further analyzed each BR and evaluated whether a subdivision could result in shorter time limits.

We repeated this process until we satisfied the time limits of all products and could obtain no additional economic improvement (see Figure 3). We also explored possible opportunities to include direct routes between cities with a sufficiently large business volume.

Relative to the physical structure and functional configuration, we found that for two layers ($n = 2$), the cost was much higher than for three layers ($n = 3$), and we could not satisfy the shortest time limits of products within the same BR. However, using four layers ($n = 4$), we could not completely satisfy the time limits of products across BRs, and the additional layer would increase scheduling and control difficulties. Therefore, we set the number of layers to three. We also found that the function of large-scale automatic sorting should be set in the RHs. Considering that CPEL's senior management was accustomed to handling sorting in LHs in its former network, which belonged to the National Universal Postal Network, management regarded this conclusion as significant.

Technical Obstacles

Large-scale network design is complex and difficult; even its subproblems are NP-hard from a computational complexity perspective (Magnanti and Wong 1984). In our optimization model, the basic model involves a large-scale nonlinear 0-1 integer programming model (see the appendix), which presents a computational challenge in attempting to find the optimal solution.

In addition, we had to regard this project as more than a mathematical exercise. To ensure that our

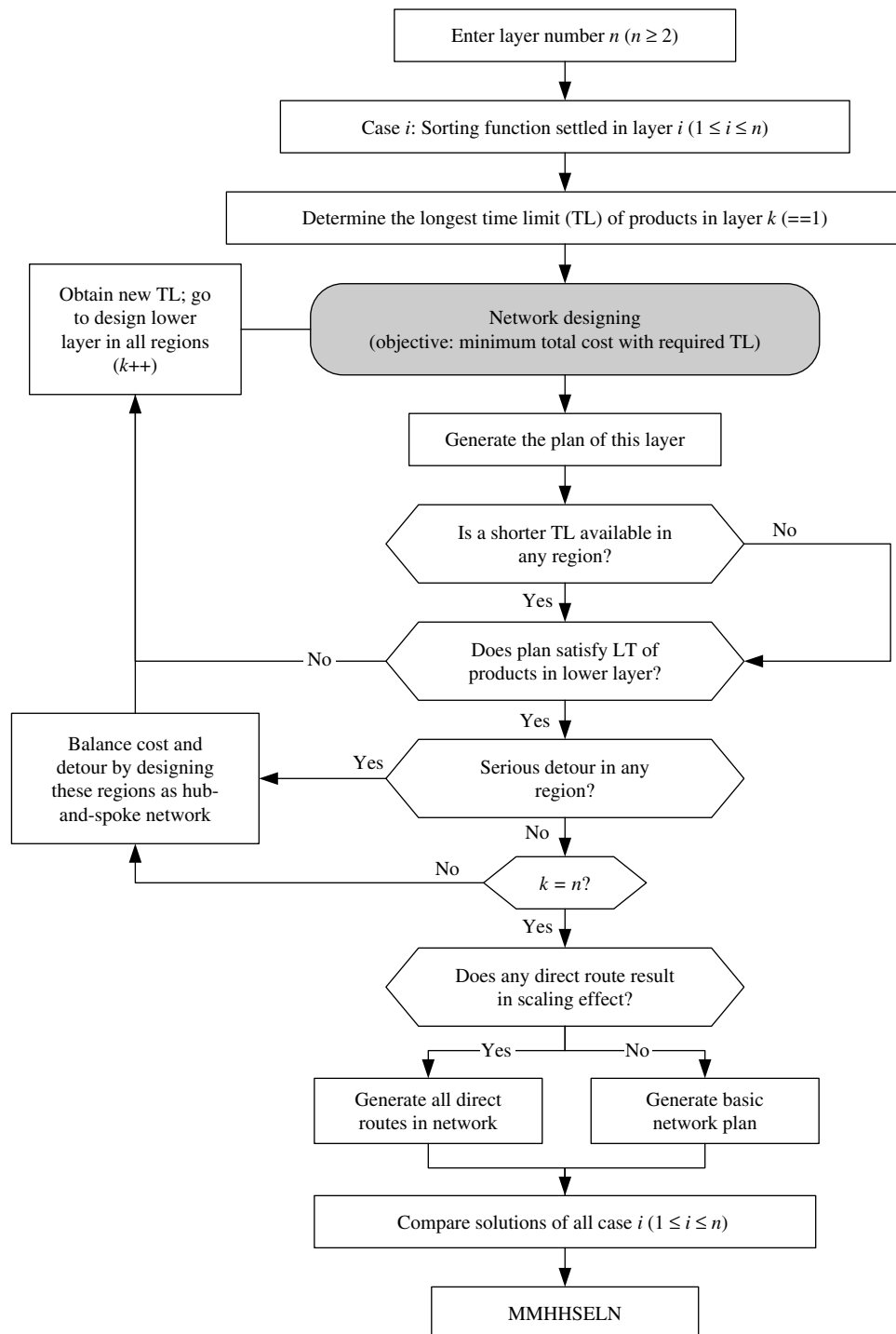


Figure 3: The flowchart shows the basic planning framework we used to design CPEL's multiproduct, multilayered hybrid hub-and-spoke express and logistics network, which we call MMHSELN.

results were applicable, the decision process had to be flexible enough to be able to include relevant practical factors. Specifically, we needed to ensure that our quantitative models would support the following issues:

- Generation of a proper optimal solution cluster.

To integrate empirical factors, such as decision-maker experience, into the decision-making process, we proposed a method to ensure that the DSS would be interactive, interruptible, and embeddable. Rather than allowing only one optimal solution, we permitted a series of near-optimal solutions that we called the optimal solution cluster. Using this cluster, we could conduct what-if analyses for different scenarios in which we include decision-maker experiences. We could then analyze the intermediate results from the enumeration process, use them to modify parameters at the next stage of the design, and integrate these soft constraints into the design.

- Relaxation of constraints for individual nodes.

Decision models usually require that all constraints be satisfied. However, in this redesign project, we found that satisfying this requirement might cause practical problems. For example, some regions in northwestern China cover large areas, and the potential hubs in these regions would be great distances from each other. If we allowed the distance from a remote city to its hub to exceed 500 kilometers (km), which CPEL often used as a standard coverage radius, we could significantly improve the result. Such modifications are more practical operationally, and the decision makers received them well. However, these methods, which include such a local relaxation of constraints in the mathematical model, had seldom been considered in research literature. Again, the interactive and interruptible capabilities of our design process made such a relaxation possible.

Decision Support System

Because of these aforementioned obstacles, the core of the planning framework (i.e., the rounded rectangle in Figure 3) required our solution to be more than solving a mathematical programming model. Therefore, we developed a DSS (the multiproduct, multilayered hybrid hub-and-spoke network design decision support system, or MMHNSDDSS) that allowed us to (1) find the optimal solution cluster, (2) present pictorial solutions directly on a map of China, (3) adjust

parameters during the decision-making process, and (4) allow individual nodes to be relaxed from their constraints. Our objective was to facilitate the scenario and what-if analyses for the decision makers.

- Algorithms

For this type of optimization problem, the most difficult task is to design proper algorithms. For solving large-scale 0-1 nonlinear programming problems, the enumeration method was our best option among the few alternatives we investigated, because it allowed us to find the optimal solution cluster. Nonetheless, its computations are time consuming. In our DSS, combined with enumeration, we designed a heuristic algorithm based on the optimal allocation principle of individual nodes: when choosing K hubs from m hub candidates, C_m^K combinations are possible. We enumerated these combinations: for a given hub combination, the nodes choose their affiliated hubs based on minimizing their own total transportation cost. We then calculated the cost of this hub combination and its allocation. Finally, we determined the optimal network design plan by comparing the costs.

In addition to the heuristic algorithm, we tried another method for a large-scale problem. This method, which differs from the traditional p HM model (O'Kelly 1987), has two basic principles: (1) Cluster cities according to their express volume, total volume of retail sales, logistics volume, and population, ensuring that the nodes in the same cluster are consecutive in geography. This is a two-dimensional ordered-clustering method based on the K -means clustering algorithm. (2) After clustering BRs based on this method, locate the corresponding PH for each BR. In practice, this approach greatly reduced the computation time.

- Preprocessing

Before solving the problem with the aforementioned algorithms, we note that if the number of nodes and hub candidates is large, the possible combinations will also be large; however, the research on solving this type of network design model shows that more than 90 percent of the feasible solutions cannot be implemented in practice; thus, the associated large computation workload is wasted. As a counter measure, we met with CPEL managers and quantified their empirical factors as the criteria to use to refine the sets of the hub candidates prior to the

enumeration. For example, we initially considered the coastal city of Xiamen as a hub candidate because of its geographical location and economic development; however, CPEL managers suggested that we exclude it as a hub because of its climate. This approach reduced the number of the hub candidates from 127 to 72.

Results

We conducted 10 large-scale seminars to discuss our potential solutions with all members of CPEL's related planning departments. Before we finalized our proposal, we presented hundreds of draft solutions, and compared and analyzed the results and trade-offs of each potential solution.

Our final solution included a three-layer network composed of eight PHs, 19 RHs, and 127 LHs. The first layer consists of eight PHs that represent a fully connected network. Each PH supervises a BR; thus, it has responsibility for distributing the long time-limit products within the BR and transferring the products between this BR and others. Each BR represents the second layer of the network and is subdivided into one or more regions. Within a BR, all corresponding RHs are fully connected. The third layer of the network, which is within a region, is a single-hub hybrid hub-and-spoke network. The core function of sorting is in the 19 RHs. This proposed network is suitable for the existing system for scheduling and control, and it is an optimal result when taking the existing network facility into consideration. Our model also improves the network's flexibility because it configures direct routes between selected cities.

Figure 4 shows an example of a local network. The structure of the first BR (upper left) is simple. This BR is the same as a region and is a two-layered network. Because the PH also functions as the only RH, it handles transferring and sorting all products within the BR and between other BRs. The second BR (lower right) has a similar structure to the BR in Figure 1. It contains three regional networks. Its PH specifically acts as one RH of these regional networks. These RHs sort the items to and from the regions and transfer the items within the regions. The long time-limit items from these regions are transferred to other BRs via the PH.

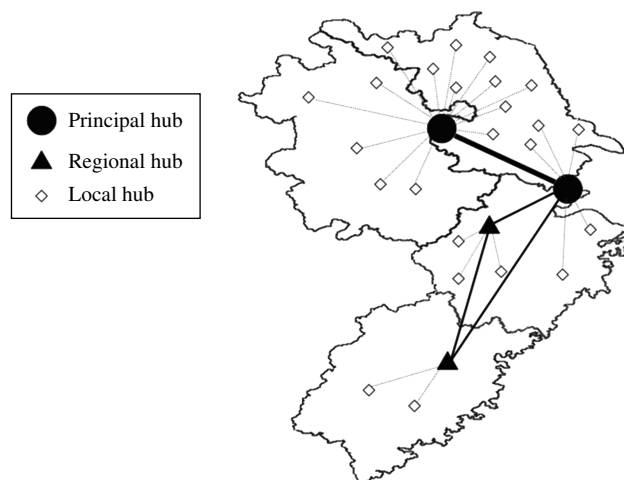


Figure 4: The map shows a network of four provinces. The upper left BR is two-layered; the lower right BR is three-layered with three regional networks that comprise a multilayered hub-and-spoke network.

Impact

Our solution met the requirements of the network redesign. Using the DSS we developed, we were able to provide solid answers to questions posed by CPEL, such as why the network should be divided into eight BRs and which cities should be set as hubs. Our suggested network structure coordinates well with the existing management system; therefore, our solution could be implemented easily.

This network redesign initially evoked divergent opinions. For example, when considering the eight PHs, we suggested Chongqing as the PH in one BR in our model; however, many CPEL managers were in favor of Chengdu as the PH in this BR. They argued that Chengdu fulfilled the transfer and distribution functions because of its transportation accessibility. However, our model gave us some insights into the system: we proposed an annual cost savings of up to \$975,000; in addition, our plan was based on the strategic development of the market in the region. After examining the respective trade-offs, the administrators in CPG's network operations department finally agreed with our opinion.

Another important but unexpected result was that our solution provided a network that could support high-end products. In particular, we identified opportunities for establishing extended intracity delivery in the central urban agglomerations of the Yangtze River

Delta, the Pearl River Delta, and the Bohai Rim. Using our network solutions in such economically developed areas, CPEL can significantly improve its service level and product range, and consequently its market competence. This result gained the attention of CPEL's managers.

Based on the calculation of our DSS, in comparison with the existing system, our proposed network can generate estimated annual operational savings of 20 percent.

In our discussions with CPEL senior management, we always stressed the importance of using an OR approach in the analysis and supported our conclusions with data and quantified measurements. Our DSS provides an overview of the network's layout and also calculates trade-offs between various alternatives in different scenarios. Moreover, the model aims to minimize costs from a system perspective. The results helped the managers analyze their problems from the perspective of the entire network, rather than focusing on a specific region or area, which in turn brought managerial insights into the network operations.

Therefore, we emphasize that in addition to the technical achievements (i.e., providing solutions), this project supported CPEL's management team by clearly and thoroughly helping it to recognize OR's role and value in decision making. We illustrated how an OR approach can provide support for analyzing and constructing a large-scale service network. This project has motivated CPEL to rely on OR in its decision-making processes. This transition has also been reflected in subsequent projects. CPEL is interested in using an OR methodology for optimizing its air and land integrated network and for designing large intracity networks.

Concluding Remarks

Based on CPEL's requirements, we redesigned its land express network by integrating existing facilities. CPEL approved our project results in which we (1) analyzed and predicted the demand distribution of the domestic express market, (2) identified the key cities and the key markets, and (3) established CPEL's strategic layout. CPEL recognized that the study results reflect the characteristics of its network, and that the proposed time-limit based design

framework and the corresponding MMHNSNDDSS are of great value for the CPEL network redesign and operations.

Implementing the proposed network solution will require significant time. Because of dynamic changes in the business and economic environment, CPEL will need to continuously test and revise solutions during this process by incorporating updated data. Therefore, it has included us in the implementation process to provide the appropriate modifications and execute the solutions. By October 2012, CPEL completed the following major implementation milestones:

- (1) Determination of PH capability scales;
- (2) expansion of the eight PHs;
- (3) configuration of the sorting function from the former LHs to the new RHs in selected pilot cities.

During this project, we encountered many challenges in applying an OR methodology, including the soft constraints, computation time, and data collection issues. In our opinion, verifying the models is critically important. We kept ongoing communications between our OR team and CPEL managers to foster mutual understanding of the modeling purpose and results, which is a key factor in assuring the successful application of OR in practice. We conclude this paper with comments from two CPEL senior managers.

YanJun Zhang, CPG Director of Network Operations states: This project is based on a thorough comprehension of China Postal Network's complex system and enhances our understanding of scientific management in the express and logistics industry.

Gang Dai, CPEL Operations Manager states: This is a solution that we have desired but to which we have had no access. It has provided an answer to our puzzle and has broken through the existing rules concerning management and control under China's district plan. The result of this project will have a significant impact on our future network operations and design.

Appendix

In the core module of this planning framework (i.e., the rounded rectangle in Figure 3), we needed to construct the following mathematical model:

Basic Nonlinear 0-1 Integer Programming Model

$$\min \left\{ \sum_{i \in L, o \in H} \sum_{j \in L} c_0(w_{ij}^{(1)} + w_{ij}^{(2)})d_{io}^{(0)}x_{io} \right. \\ \left. + \sum_{i, j \in L, h_o, h_d \in H} (c_t d_{h_o h_d}^{(t)} w_{ij}^{(1)} + c_a d_{h_o h_d}^{(a)} w_{ij}^{(2)})x_{ih_o}x_{jh_d} \right.$$

$$\begin{aligned}
& + \sum_{h \in H} \sum_{i, j \in L} s_h \left(\sum_{i, j \in L} (q_{ij}^{(1)} + q_{ij}^{(2)}) x_{ih} \right) (q_{ij}^{(1)} + q_{ij}^{(2)}) x_{ih} \\
& + \frac{1}{m} \sum_{h \in P} C_h \left(\sum_{i, j \in L} (q_{ij}^{(1)} + q_{ij}^{(2)}) x_{ih} \right) x_{hh} \\
& + \sum_{h \in H} O_h \left(\sum_{i, j \in L} (q_{ij}^{(1)} + q_{ij}^{(2)}) x_{ih} \right) x_{hh} - \sum_{h \in E} t_h x_{hh} \Big\} \\
\text{s.t. } & \begin{cases} \sum_{h \in H} x_{ih} = 1, & i \in L; \\ x_{ih} \leq x_{hh} (i \in L), & h \in H; \\ \sum_{h \in H} x_{hh} = K \\ \sum_{h_o, h_d \in H} d_{ij}^{(0)} x_{ih_o} x_{jh_d} \leq D_1, & i, j \in L; \\ \max_{i \in L} \{d_{ih} x_{ih}\} \leq D_2, & h \in H; \\ \sum_{h_o, h_d \in H} d_{h_o h_d}^{(t)} x_{ih_o} x_{jh_d} \geq D_3, & i, j \in L; \\ x_{ih} = \{0, 1\}, & i \in L, h \in H. \end{cases}
\end{aligned}$$

Index Sets

$L = \{i \mid i = 1, 2, \dots, n\}$: All key cities of the current network.
 H : Set of hub candidates, and $H \subseteq L$.
 E : Set of existing hubs.

Decision Variables

x_{ij} : 0-1 integer variable. When City i takes City j as its hub, $x_{ij} = 1$; otherwise, $x_{ij} = 0$, $\forall i \in L, \forall j \in H$.

Costs

c_0 : Unit cost of transporting express items between nonhub cities by truck.
 c_t : Unit cost of transporting items between hub cities by train; usually, $c_t = \delta c_0$ ($0 < \delta < 1$).
 c_a : Unit cost of transporting items between hub cities by air.
 $s_i(q)$: Sorting cost function in hub i ($i \in H$); The variable q is the annual total number of items.
 $C_i(q)$: Construction cost function of hub i ($i \in H$); the variable q is the annual total number of items.
 $O_i(q)$: Annual operations cost function in hub i ($i \in H$); the variable q is the annual total number of items.

(Note that we omit costs for picking up and delivering express items because they are unrelated to the decision.)

Parameters

m : Investment recovery years of the fixed costs.
 $d_{ij}^{(k)}$: Distance between cities i and j by truck ($k = 0$), by train ($k = t$), or by air ($k = a$), $i, j \in L$.

S : The set of express product types; the superscript $S = 2$ represents next-morning, next-day, and second-day deliveries; $S = 1$ represents the other product types.

t_h : Value of the existing hub, $h \in E$.

$q_{ij}^{(S)}$: Total express item pieces of product S from city i to city j , $i, j \in L$.

$w_{ij}^{(S)}$: Total express item weight of product S from city i to city j , $i, j \in L$.

K : Given number of hubs.

D_1 : Maximum distance of delivering short-time-limit express items by the land express network. Alternatively, if the distance is beyond D_1 , the item must be delivered by air.

D_2 : Maximum coverage radius of a hub.

D_3 : Minimum distance between hubs.

In the objective function, the first item is the annual total transport cost between hubs and nonhubs; the second item is the total transportation cost between hubs; the third item is the annual sorting cost; the fourth item is the average annual construction cost; the fifth item is the annual operation cost; and the last item is the total rest value of the existing hubs, which have been selected as hubs in the redesigned network. The cost functions, $s_i(q)$, $C_i(q)$, and $O_i(q)$, in any city come from considering factors such as land price and labor wage level.

The first constraint ensures that any one node is charged by only one hub. The second constraint ensures that any hub is charged by itself. The third constraint indicates that the network has K hubs. The fourth constraint reflects that the land express network has a maximum distance for delivering short-time-limit products; that is, if the distance exceeds D_1 , then the air network should be used. The fifth constraint limits the hub's maximum service radius, which is determined by the shortest time limit in the region. The sixth constraint indicates the shortest distance between hubs.

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Verification Letter

Ning Xu, Manager of Development Department, China Postal Express and Logistics Corporation, Num. 410, Fuchengmen Street, Beijing 100034, China, writes:

“I hereby state that I would like to confirm that Dr. Jianjun Zhang and his team from Tongji University have helped us redesign the land express network. The corresponding project “Redesigning CPEL’s land express network” began in August, 2008 and ended at December, 2010, and the results of this project were approved by our top management.”

Jianjun Zhang is an associate professor of management science and engineering at Tongji University, China, where he obtained a PhD in 2008. His research is supported by National Natural Science Foundation of China and Shanghai Rising-Star Program. His research interests are in the areas of logistics network designing, supply chain coordination, supply chain risk management, and service operations management.

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