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A hybrid hub-and-spoke postal logistics network with realistic restrictions: A case study of Korea Post

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ABSTRACT

Postal logistics has a complex transportation network for efficient mail delivery. Therefore, a postal logistics network consists of various functional sites with a hybrid hub-and-spoke structure. More specifically, there are multiple Delivery & Pickup Stations (D&PSs), multiple Mail Processing Centers (MPCs), and one Exchange Center (EC). In this paper, we develop two mathematical models with realistic restrictions for Korea Post for the current postal logistics network by simultaneously considering locations and allocations. We propose an Integer Linear Programming (ILP) model for transportation network organization and vehicle operation and a Mixed Integer Linear Programming (MILP) model that considers potential ECs for decision making while simultaneously regarding the EC location, transportation network organization, and vehicle operation. We use modified real data from Korea Post. Additionally, we consider several scenarios for supporting EC decision makers. The proposed models and scenarios are very useful in decision making for postal logistics network designers and operators.

1. Introduction

In Korea, mail operation machines and indoor transportation facilities, such as conveyors and sorting machines, are supplied to the main post offices to improve the productivity of mail operations. To raise the efficiency of the entire postal operation, Korea Post has promoted mechanization since 1985. However, the construction of mail processing centers (MPCs) is capital-intensive regarding the mechanization and automation of logistics; thus, it is difficult to change the mail logistics scheme. It is necessary to develop a strategy for radically changing logistics processes over and beyond the efficiencies of individual nodes in the logistics network. In this respect, a hub-and- spoke scheme is a major enabler of integration strategies in mail logistics. For radical changes in mail logistics, the scheme was redesigned to comprise one EC (Exchange Center) and 25 MPCs. A hybrid hub-and-spoke system involves a single EC as a hub and transport between the EC and the 25 MPCs as well as between the 25 MPCs. This approach towards mail logistics has shifted mail from rail freight to road freight. Twenty-five MPCs and one EC are currently involved in the automated dispatching and sorting operations through the network of MPCs (Fig. 1).

For hub-and-spoke transportation systems, we must identify both strategic and operational decisions. The strategic decisions for a hub-and-spoke transportation system include the following: the selection of suitable locations for consolidation, the assignment of customers to sending and receiving depots, the determination of line-haul routes, and the choices of the types of transportation facilities. Operational decisions, which are based on strategic decisions, include the disposition of the number of vehicles for line-haul, and the planning of pick-up and delivery tours for parcels or part-loads to the customers from each depot (Zäpfel & Wasner, 2002).

Increased competition in the transportation market has led to new cooperative arrangements between third-party logistics providers in the form of hub-and-spoke systems. In addition to the design problem, operational planning for a hub-and-spoke network is a challenging task for the management of such transportation networks. Specifically, transportation management has to decide whether a pure hub-and-spoke system should be implemented, where all of the quantities within the transportation network flow over the hub to and from the depots, or whether a hybrid hub-and-spoke network is preferred in which direct transportation also takes place.

The network problem occurs in postal logistics is very complex and diverse. Moreover, the amount of data is enormous which makes the decision makers difficult to design the network. In

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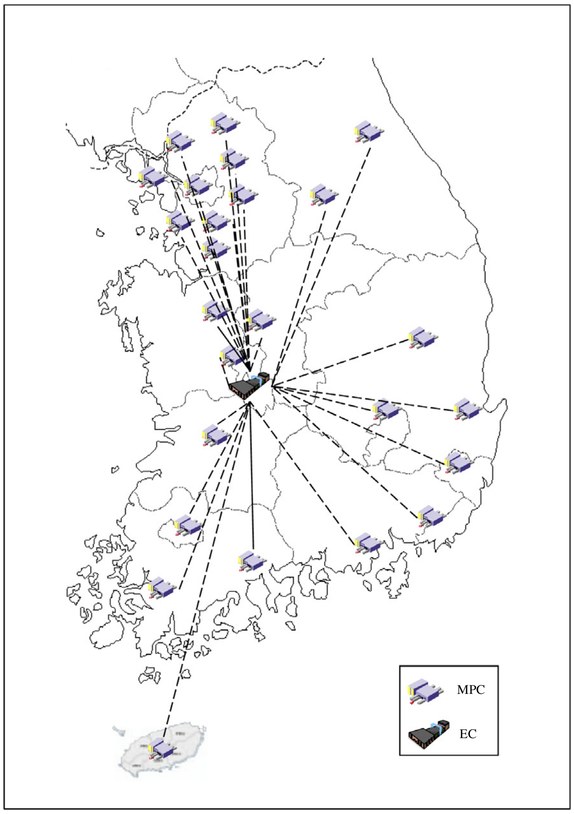

Fig. 1. Current automated facilities in the postal logistics network.

postal logistics, the efficient design and operation of the transportation network is a very important issue. However, it is difficult to flexibly operate the postal logistics network according to changes in the mail volume. In the Korea Post, a transportation plan is pre-determined and the transportation of mail is performed through the routes in the plan. When the routes cannot transport all of the mail, temporary vehicles are used. In postal transportation, it is important to develop a good transportation plan and to efficiently manage the plan. However, it is difficult to change the transportation plan because hundreds of vehicles are involved; thus, planning is required in advance.

Today, Korea Post is actively participating in the nationwide green movement, attempting to transform itself into a more environmentally friendly business by declaring the "2020 Green Post" strategy. They are already prepared for new laws on green growth and for cuts in greenhouse gas emissions, as well as for energy saving policies of government agencies. The postal business has an interest in green logistics, needing to meet the government's requirements. Especially, the delivery vehicle problem is associated with the postal logistics network. Therefore, the results of this paper can be usefully applied to postal logistics.

2. Literature review

The efficient design and operation of transportation networks is a very important issue (Lee, Moon, & Park, 2010). Recently, research has highlighted simulation technology that can model realistic problems and enables quantitative analysis (Ding, Benyoucef, & Xie, 2009; Kim et al., 2003; Wert, Bard, deSilva, & Feo, 1991). However, existing research results are focused on the development of simulations to support decision making from a broad perspective. Therefore, in some circumstances and especially in postal logistics networks, the development of simulations that reflect real situations cannot be accomplished (Cheung & Bal, 1998).

The implementation of hub networks is performed to consolidate flows from different origins and to ship them via hubs to different destinations, thus reducing total transportation costs. In hub networks, all of the hubs are interconnected, and none of the non-hubs are directly connected to each other. Each of the non-hub nodes is allocated to either multiple hubs or a single hub. Many studies have shown that the implementation of hub networks can lower total transportation costs, and successful applications of hub networks have arisen in many areas (Abdinnour-Helm, 2001; Bania, Bauer, & Zlatoper, 1998; De Camargo & Miranda, 2012; Elhedhli & Hu, 2005; Klincewicz, 1998; Kuby & Gray, 1993).

For strategic decision problems concerning hub-and-spoke systems, considerable literature is available. O'Kelly (1986, 1987) was the first to examine the problem of designing hub-and-spoke systems through the formulation of a quadratic programming problem. Because the number of possible sets of hub locations increases exponentially with the size of the problem, the proposed solution method is limited to small-scale transportation networks. Some researchers have decomposed the hub-location problem into two sub-problems (hub location and routing) and applied different solution methods. Skorin-Kapov and Skorin-Kapov (1994) used tabu search to find good solutions for each sub-problem. Aykin (1995) investigated two different variants of the hub design problem. In the first variant, all of the traffic from a given point must flow through a specific hub before proceeding to its destination. The second variant permits trips from a given origin to different hubs depending on the destination. Aykin (1995) developed an enumeration method for multiple allocations and a branch-and-bound method for the single allocation case. Campbell (1996) proposed heuristics that rely on first solving the multiple assignment problems via a greedy exchange method and then using this solution to develop a network of hubs and allocations for the single assignment problem. A more comprehensive review of mathematical modeling for hub design can be found in several studies (Campbell, 1994; O'Kelly & Miller, 1994; O'Kelly et al., 1997).

The general operational decisions in hub-and-spoke systems have received little attention in the literature, although many publications address a related problem. Specifically, the incorporation of direct transportation in pure hub-and-spoke systems was discussed in Lumsden, Dallari, and Ruggeri (1999). These authors provided an overview of hub-and-spoke systems and proposed some possible improvements to this practice for freight transportation.

Lumsden et al. (1999) improved upon the pure hub-and-spoke system. Specifically, they applied the re-allocation of transportation resources and direct connections between pairs of nodes in the distribution network in a case study. All of the aspects of feasibility were discussed, and alternative solutions were compared to the present configuration in terms of the average lead times, the flow of goods, truck utilization rates, and transportation costs. Zäpfel and Wasner (2002) noted that transportation management has to decide whether a pure hub-and-spoke system should be implemented, where all of the quantities within the transportation network flow over the hub from or to the depots, or whether a hybrid hub-and-spoke network is preferred in which direct transportation also takes place. Taha, Taylor, and Taha (1996) presented a simulation-based software system for evaluating hub-and-spoke transportation networks. Park, Lee, Choi, and Lee (2005) developed a simulation model to evaluate the performance of a postal transportation plan in Korea Post. Liu, Li, and Chan (2003) proposed a mixed truck delivery system and a heuristic algorithm with hub-and-spoke and direct shipment delivery. Recently, the hub-and spoke design for the container ship network can be found in several studies (Gelareh, Maculan, Maheye, & Monemi, 2013; Konings, Kreutzberger, & Maraš, 2013).

Table 1
Comparison of the methodology and consideration of this paper with previous studies.

Methodology	Consideration		
	Pure hub-and-spoke	Hybrid hub-and-spoke	Destination
Mathematical programming	O'Kelly (1986, 1987)	This paper	
	Aykin (1995)	Werners and Wulfing (2010)	X
Heuristic or simulation	Skorin-Kapov and Skorin-Kapov (1994)	Lumsden et al. (1999)	X
	Campbell (1996)		
	Taha et al. (1996)	Liu et al. (2003)	
	Cunha and Silva (2007)	Park et al. (2005)	
	Konings et al. (2013)	Moreno-Quintero (2006)	
	Gelareh et al. (2013)		

In recent years, some studies have considered more realistic situations. Moreno-Quintero (2006) focused on a road planner that provides the infrastructure for the paved network in Mexico. Cunha and Silva (2007) discussed the problem of configuring hub-and-spoke networks for trucking companies that operate less-than-truckload (LTL) services in Brazil. The proposed formulation differs from similar formulations found in the literature in the sense that it allows variable scale-reduction factors for the transportation costs according to the total amount of freight between hub terminals, as occurs for less-than-truckload (LTL) freight carriers in Brazil. Wagner (2008) proposed an improved model formulation for hub covering problems with multiple and single allocation problems, including non-increasing, quantity-dependent, transport time functions for transport links for the single allocation case. Lin and Chen (2008) presented a generalized hub-and-spoke network in a capacitated and directed network configuration. They developed an implicit enumeration algorithm and tested it using the FedEx AsiaOne air network. Alumur and Kara (2009) focused on cargo applications of the hub location problem in the Turkish cargo sector. They proposed a new mathematical model for the hub location problem that relaxes the complete hub network assumption considering a time limitation. Lee, Gen, and Rhee (2009) formulated a mathematical model of a multi-stage reverse logistics network problem that considered shipping costs and inventory holding costs. They proposed a hybrid GA (Genetic Algorithm) that combined a priority-based GA using WMX (Weight Mapping Crossover) and a heuristic. Wanitwattanakosol, Holimchayachotikul, Nimsrikul, and Sopadang (2010) proposed a two-phase quantitative framework using a simulation and AHP (Analytic Hierarchy Process) for the effective selection of an efficient freight logistics hub in Thailand. Werners and Wulfing (2010) demonstrated that significant reductions in internal transportation at one of the Deutsche Post World Net's main parcel sorting centers could be achieved by applying the robust solution of a modified three-dimensional linear assignment model. Blagojević, Šelmić, Macura, and Šarac (2013) suggested the new approach for determining the required number of permanent postal units using well known Wang–Mendel's (WM's) method on real data collected from Serbian municipalities. Table 1 summarizes the comparison of the methodology and consideration of this paper with previous studies.

The remainder of this paper is organized as follows. Section 3 proposes mathematical models that consider realistic restrictions. In Section 4, we show numerical examples for the developed models and present computational experiments for the application of decision making. Finally, we present our conclusions in Section 5.

3. Mathematical models

The postal logistics network of Korea Post employs a hybrid hub-and-spoke network that is composed of 220 D&PSs (Delivery & Pickup Stations), 25 MPCs, and 1 EC. Mail that is collected from D&PSs is transported to a sending MPC. After the mail is sorted, it is transported to a receiving MPC. The transportation of mail between D&PSs and MPCs constitutes the D&PC network, and the transportation of mail between MPCs constitutes the MPC network. Finally, the transportation of mail between MPCs and the EC constitutes the EC network.

We develop mathematical models for a postal logistics network (a hybrid hub-and-spoke system). Specifically, transportation management has to decide whether a hub-and-spoke system should be realized, where all of the quantities within the transportation network flow over the hub from or to the depots, or whether a hybrid hub-and-spoke network is preferred in which direct transportation also takes place. For strategic decision making in this system, we consider a network of MPCs and an EC.

In Korea, the post office has three types of logistics networks, which can be categorized according to their functions (Fig. 2). Approximately 220 post offices (D&PS; thin dotted lines) undertake the receiving and delivery of business mail (D&PS network). Twenty-five post offices sort mail and send it to other post offices (MPC network; bold lines) and one post office (EC) exchanges mail only (i.e., plays the role of a distribution center in a supply chain) to accomplish efficiency of the transportation (EC network; bold dotted lines).

Postal logistics network models can be defined by the following assumptions:

- We consider 24 MPCs and one EC (one MPC is excluded among the 25 MPCs, because one MPC which is located on an island cannot be accessed by land vehicles).
- We consider small-sized mail (general small letters).
- We consider an annual mail quantity.
- There are two delivery modes: direct delivery mode between MPCs and exchange delivery mode between MPCs and EC (hybrid hub-and-spoke network).
- The received mail quantity is known in advance.
- The destination of an item of mail is known in advance (when receiving the mail).

3.1. PLN (postal logistics network) Model 1

Model 1 corresponds to the current postal logistics network that is similar to a general three-level supply chain network. However, the postal logistics network is a hybrid hub-and-spoke

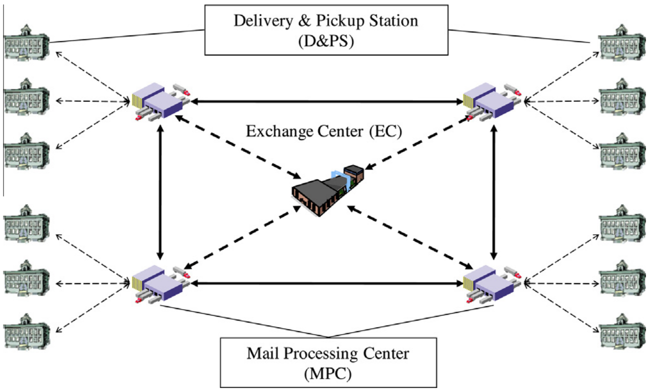

Fig. 2. Three types of network structures in postal logistics.

system that simultaneously uses direct transportation and hub-and-spoke transportation, where the hub is the EC and the spokes are the MPCs. In Model 1, we consider the distances from MPCs to the EC and the capacity of the EC. Particularly, we consider the transportation rate from the sending MPC (MPC i) to the receiving MPC (MPC j); the destination location is determined when the mail is received. We also consider the vehicles and their capacities. We use only 11-ton vehicles between MPCs and between MPCs and the EC. A vehicle can carry 255,000 mail items (17 pallets and 15,000 mail items per pallet). Even though the mail quantities are less than 255,000, we have to assign one vehicle (which lowers the vehicle efficiency). If the sending and receiving MPCs are identical, there is no need for a vehicle. An additional restriction for an efficient transportation strategy regarding the operation of MPCs and the EC is that if the receiving mail is less than the capacity of a vehicle, then we have to send the mail to the EC. The objective is to minimize the sum of the transportation costs and fixed vehicle costs. The notation is given below:

Indices	
I, J	set of MPCs
K	set of ECs
i, j	indices of MPCs ($i \in I, j \in J$)
k	index of ECs ($k \in K$)
Parameters	
(1) Transportation distances (km)	
dmc_{ij}	transportation distance from MPC i to MPC j, for all $i \in I, j \in J$
dme_{ik}	transportation distance from MPC i to EC k, for all $i \in I, k \in K$
dem_{kj}	transportation distance from EC k to MPC j, for all $j \in J, k \in K$
(2) Transportation costs (₩; Korean won)	
$tcmc_{ij}$	unit transportation cost from MPC i to MPC j, for all $i \in I, j \in J$
$tcme_{ik}$	unit transportation cost from MPC i to EC k, for all $i \in I, k \in K$
$tcem_{kj}$	unit transportation cost from EC k to MPC j, for all $j \in J, k \in K$
(3) Fixed costs of vehicles (₩; Korean won)	
vmc_{ij}	fixed cost for a vehicle from MPC i to MPC j, for all $i \in I, j \in J$
vme_{ik}	fixed cost for a vehicle from MPC i to EC k, for all $i \in I, k \in K$
vem_{kj}	fixed cost for a vehicle from EC k to MPC j, for all $j \in J, k \in K$
(4) Conversion coefficient	
cc	coefficient for converting quantities into numbers of vehicles (255,000)
(5) Capacity (pieces)	
cap_k	annual exchange capacity at EC k
(6) Quantity and rate	
s_i	annual mail quantity (pieces) collected at MPC i, for all $i \in I$
r_{ij}	annual transportation rate from MPC i to MPC j, for all $i \in I, j \in J$
Decision variables	
X_{ij}	annual direct transportation quantity from MPC i to MPC j, for all $i \in I, j \in J$
Y_{ik}	annual exchange transportation quantity from MPC i to EC k, for all $i \in I, k \in K$
Z_{kj}	annual exchange transportation quantity from EC k to MPC j, for all $j \in J, k \in K$
$NVMC_{ij}$	number of vehicles from MPC i to MPC j, for all $i \in I, j \in J$
$NVME_{ik}$	number of vehicles from MPC i to EC k, for all $i \in I, k \in K$
$NVEM_{kj}$	number of vehicles from EC k to MPC j, for all $j \in J, k \in K$

We present two mathematical models with realistic restrictions. In Fig. 3, we describe the notation used for mathematical modeling.

The ILP model for Model 1 is presented as follows:

$$\begin{aligned} MIN & \sum_{i \in I}\sum_{j \in J} tcmc_{ij} \cdot dmc_{ij} \cdot X_{ij} + \sum_{i \in I}\sum_{k \in K} tcme_{ik} \cdot dme_{ik} \cdot Y_{ik} \\ & + \sum_{k \in K}\sum_{j \in J} tcem_{kj} \cdot dem_{kj} \cdot Z_{kj} + \sum_{i \in I}\sum_{j \in J} vmc_{ij} \cdot NVMC_{ij} \\ & + \sum_{i \in I}\sum_{k \in K} vme_{ik} \cdot NVME_{ik} + \sum_{k \in K}\sum_{j \in J} vem_{kj} \cdot NVEM_{kj} \end{aligned} \tag{1}$$

subject to

$$\sum_{i \in I} Y_{ik} - \sum_{j \in J} Z_{kj} = 0, \quad \text{all } k \in K \tag{2}$$

$$\sum_{j \in J} X_{ij} + \sum_{k \in K} Y_{ik} = s_i, \quad \text{all } i \in I \tag{3}$$

$$\sum_{i \in I} X_{ij} + \sum_{k \in K} Z_{kj} = \sum_{i \in I} s_i \cdot r_{ij}, \quad \text{all } j \in J \tag{4}$$

$$X_{ij} = s_i \cdot r_{ij} \ (\text{if } s_i \cdot r_{ij} \geqslant cc), \quad \text{all } i \in I, j \in J \tag{5}$$

$$\sum_{i \in I} Y_{ik} \leqslant cap_k, \quad \text{all } k \in K \tag{6}$$

$$X_{ij} - cc \cdot NVMC_{ij} \leqslant 0, \quad \text{all } i \in I, j \in J (i \neq j) \tag{7}$$

$$NVMC_{ij} = 0, \quad \text{all } i \in I, j \in J (i = j) \tag{8}$$

$$Y_{ik} - cc \cdot NVME_{ik} \leqslant 0, \quad \text{all } i \in I, k \in K \tag{9}$$

$$Z_{kj} - cc \cdot NVEM_{kj} \leqslant 0, \quad \text{all } k \in K, j \in J \tag{10}$$

$$\begin{aligned} & X_{ij}, Y_{ik}, Z_{kj}, NVMC_{ij}, NVME_{ik}, NVEM_{kj} \\ & N: \text{Non} - \text{negative integer}, \quad \text{all } i \in I, j \in J, k \in K \end{aligned} \tag{11}$$

The objective function (1) minimizes the sum of the transportation costs and fixed costs for using the vehicles. The transportation costs consist of the cost of transporting from the sending MPC i to the receiving MPC j, from the sending MPC i to EC k, and from EC k to the receiving MPC i. Constraints (2)-(4) are the flow conservation constraints. Constraint (2) specifies that the transported quantities from the sending MPC to the EC are equal to the quantities that are transported from the EC to the receiving MPC. Constraint (3) specifies that the sum of the directly transported quantities from the sending MPC to the receiving MPC and the transported quantities from the sending MPC to the EC are equal to the collected mail quantities at the sending MPC. Constraint (4) represents the flow conservation constraints whereby the sum of the directly transported quantities from the sending MPC to the receiving MPC and the transported quantities from the EC to the receiving MPC are equal to the sum of the collected mail quantities at the receiving MPC multiplied by the transportation rate from the

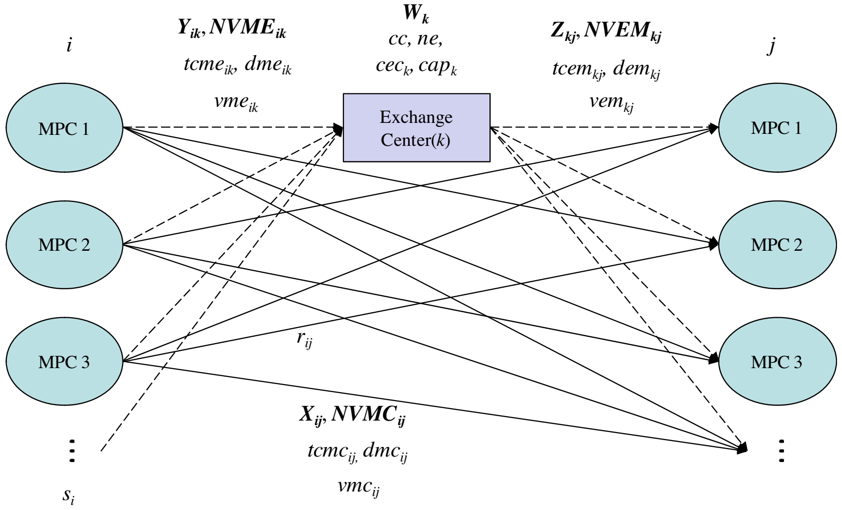

Fig. 3. Description of the notation used.

Table 2
Distance matrix from MPC i to MPC j (dmc_{ij}, km).

i	j																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	234	414	285	274	203	341	233	215	208	205	447	196	220	480	295	119	214	318	387	375	226	224	236
2	234	0	307	296	181	33	390	17	22	50	56	346	254	38	371	0	132	36	210	346	373	108	150	355
3	415	307	0	213	143	287	245	297	291	263	255	91	288	275	77	309	297	313	103	162	213	205	194	290
4	290	296	213	0	157	265	96	291	276	253	249	187	91	269	288	102	209	286	190	115	100	205	161	79
5	273	181	143	157	0	162	248	171	165	138	129	182	169	149	211	256	155	188	47	182	226	78	52	233
6	203	33	288	266	162	0	360	31	13	25	37	327	222	23	352	352	100	28	192	327	343	90	128	323
7	342	389	244	95	248	358	0	384	369	346	343	162	184	362	283	66	303	380	232	91	38	296	253	112
8	233	17	297	290	171	31	384	0	19	45	46	335	247	28	360	377	128	43	200	336	365	98	140	348
9	215	22	290	276	164	13	370	20	0	29	39	329	233	17	354	362	112	31	194	329	353	91	133	335
10	208	50	263	252	138	24	346	45	29	0	12	302	208	19	327	338	94	50	167	303	329	65	105	310
11	206	56	255	250	130	36	344	46	39	12	0	294	206	24	319	336	92	62	159	295	324	57	99	308
12	447	346	91	187	182	326	162	336	329	302	294	0	266	314	122	226	329	352	137	78	130	244	226	264
13	201	253	289	91	169	222	185	246	233	208	205	266	0	224	364	160	134	243	207	193	181	180	147	111
14	221	38	275	269	150	24	363	28	19	20	24	314	225	0	339	355	107	47	179	315	344	76	118	327
15	480	371	78	288	210	351	284	362	355	328	319	122	362	339	0	347	362	378	169	200	252	269	260	365
16	294	382	307	102	256	351	66	378	362	339	336	226	160	355	347	0	287	373	285	155	102	296	252	65
17	119	131	296	209	155	100	303	128	111	94	91	329	133	106	362	287	0	113	200	291	287	112	106	243
18	214	35	314	286	188	28	380	43	31	50	62	352	242	46	377	372	112	0	217	348	363	115	146	345
19	318	211	104	191	47	190	233	200	194	167	158	137	208	178	171	286	200	217	0	0	200	108	97	267
20	389	346	161	114	182	326	91	336	330	303	294	78	193	314	200	155	290	348	154	0	59	244	206	191
21	376	372	213	99	227	341	38	365	352	329	322	131	181	342	252	103	287	363	201	60	0	275	231	146
22	227	108	205	204	78	88	295	98	91	65	56	244	180	76	269	295	113	115	109	245	275	0	47	269
23	223	150	193	161	52	126	252	139	133	105	97	226	148	117	260	252	105	146	97	206	231	47	0	225
24	236	352	287	76	230	320	109	347	332	309	305	261	109	325	363	63	242	342	263	188	145	269	225	0

Table 3
Distance matrix between MPCs and the current EC (dme_{ik}, dem_{kj}, km).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
EC 1	219	145	115	126	0	129	199	137	132	110	104	145	135	119	168	205	124	150	37	146	181	63	42	186

sending MPC to the receiving MPC. Constraint (5) specifies that the directly transported quantities are equal to the collected mail quantities multiplied by the transportation rate, if the collected mail quantities multiplied by the transportation rate is more than the conversion coefficient. Constraint (6) specifies that the transported quantities from the sending MPC to the EC cannot exceed the EC's capacity. Constraints (7), (9), and (10) specify that the transported quantities (from MPC to MPC, from MPC to EC, and from EC to MPC, respectively) cannot exceed the product of the conversion coefficient and the number of vehicles used. Constraint (8) means that if the sending and receiving MPCs are identical, a vehicle is not needed. Constraint (11) ensures that all of the decision variables assume non-negative integers.

3.2. PLN (postal logistics network) Model 2

In Model 2, we consider the potential ECs. The objective is to minimize the sum of the transportation costs, fixed vehicle costs, and fixed costs of opening the ECs. In addition to the notation for PNL Model2, additional notation is introduced, as follows:

Table 4
Matrix of transportation rates from MPC i to MPC j (r_{ij}).

i	j 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.103	0.048	0.015	0.025	0.041	0.092	0.025	0.066	0.060	0.062	0.034	0.005	0.009	0.046	0.004	0.017	0.191	0.067	0.016	0.006	0.013	0.017	0.019	0.019
2	0.010	0.040	0.028	0.041	0.037	0.111	0.054	0.102	0.084	0.078	0.040	0.013	0.012	0.065	0.011	0.027	0.019	0.081	0.055	0.016	0.024	0.019	0.019	0.014
3	0.003	0.021	0.440	0.011	0.019	0.048	0.017	0.035	0.036	0.023	0.011	0.099	0.002	0.026	0.105	0.005	0.006	0.024	0.039	0.005	0.008	0.008	0.006	0.003
4	0.007	0.025	0.011	0.208	0.028	0.076	0.064	0.047	0.051	0.039	0.019	0.006	0.086	0.030	0.004	0.038	0.014	0.029	0.010	0.026	0.032	0.010	0.012	0.128
5	0.013	0.033	0.030	0.041	0.138	0.066	0.044	0.066	0.036	0.036	0.036	0.019	0.012	0.032	0.013	0.024	0.025	0.049	0.041	0.015	0.032	0.116	0.076	0.007
6	0.007	0.050	0.019	0.034	0.025	0.299	0.042	0.068	0.069	0.076	0.033	0.009	0.007	0.049	0.006	0.020	0.015	0.082	0.018	0.008	0.018	0.018	0.016	0.012
7	0.008	0.025	0.020	0.064	0.026	0.041	0.173	0.042	0.028	0.034	0.021	0.013	0.014	0.036	0.008	0.143	0.013	0.051	0.016	0.050	0.124	0.010	0.014	0.026
8	0.014	0.071	0.028	0.012	0.037	0.081	0.042	0.140	0.069	0.058	0.052	0.014	0.026	0.080	0.040	0.018	0.023	0.063	0.011	0.024	0.016	0.029	0.024	0.028
9	0.016	0.049	0.017	0.021	0.007	0.008	0.067	0.043	0.266	0.104	0.025	0.016	0.007	0.028	0.068	0.019	0.017	0.039	0.021	0.035	0.056	0.015	0.046	0.010
10	0.008	0.066	0.018	0.031	0.023	0.174	0.029	0.092	0.104	0.083	0.067	0.008	0.005	0.081	0.006	0.014	0.022	0.084	0.017	0.006	0.013	0.016	0.017	0.016
11	0.008	0.070	0.012	0.015	0.021	0.077	0.018	0.114	0.052	0.172	0.042	0.006	0.006	0.155	0.006	0.009	0.024	0.109	0.014	0.007	0.016	0.025	0.015	0.007
12	0.001	0.003	0.040	0.002	0.003	0.007	0.007	0.004	0.005	0.004	0.002	0.869	0.001	0.003	0.026	0.001	0.001	0.008	0.001	0.004	0.003	0.001	0.001	0.003
13	0.007	0.034	0.005	0.207	0.025	0.068	0.044	0.052	0.049	0.033	0.015	0.007	0.046	0.038	0.002	0.027	0.018	0.038	0.005	0.008	0.013	0.010	0.016	0.233
14	0.009	0.055	0.026	0.038	0.034	0.084	0.046	0.109	0.085	0.060	0.053	0.012	0.007	0.155	0.008	0.020	0.019	0.068	0.029	0.010	0.019	0.019	0.022	0.013
15	0.001	0.010	0.098	0.004	0.004	0.020	0.006	0.015	0.014	0.009	0.004	0.013	0.001	0.011	0.760	0.002	0.003	0.009	0.003	0.003	0.002	0.002	0.002	0.004
16	0.009	0.021	0.015	0.043	0.024	0.049	0.364	0.034	0.034	0.026	0.014	0.010	0.011	0.027	0.004	0.112	0.010	0.025	0.012	0.039	0.061	0.010	0.011	0.035
17	0.116	0.049	0.008	0.022	0.022	0.095	0.021	0.083	0.046	0.088	0.053	0.005	0.011	0.052	0.003	0.013	0.129	0.096	0.012	0.004	0.018	0.012	0.032	0.010
18	0.009	0.082	0.028	0.038	0.035	0.165	0.043	0.104	0.088	0.079	0.046	0.011	0.010	0.066	0.009	0.021	0.029	0.017	0.027	0.008	0.019	0.025	0.027	0.014
19	0.008	0.041	0.152	0.026	0.088	0.065	0.032	0.079	0.052	0.038	0.034	0.034	0.009	0.037	0.019	0.017	0.019	0.043	0.096	0.027	0.021	0.027	0.024	0.012
20	0.004	0.023	0.011	0.074	0.025	0.055	0.129	0.082	0.077	0.018	0.031	0.008	0.008	0.054	0.003	0.065	0.008	0.031	0.015	0.134	0.111	0.009	0.012	0.013
21	0.004	0.017	0.011	0.046	0.017	0.029	0.240	0.023	0.028	0.020	0.015	0.008	0.007	0.018	0.007	0.088	0.009	0.022	0.016	0.174	0.173	0.008	0.007	0.013
22	0.009	0.041	0.017	0.027	0.168	0.071	0.022	0.092	0.053	0.048	0.077	0.013	0.008	0.050	0.006	0.015	0.024	0.052	0.022	0.011	0.013	0.090	0.060	0.011
23	0.010	0.035	0.019	0.031	0.132	0.081	0.030	0.069	0.053	0.055	0.038	0.009	0.013	0.049	0.005	0.017	0.073	0.054	0.021	0.010	0.026	0.056	0.101	0.013
24	0.006	0.018	0.009	0.177	0.034	0.066	0.047	0.052	0.077	0.017	0.023	0.005	0.152	0.044	0.002	0.050	0.012	0.031	0.006	0.009	0.024	0.007	0.010	0.122

Parameters

(1) Fixed cost of opening an EC (₩; Korean won)

cec_k	fixed cost of opening EC k, for all $k \in K$

(2) Given values by the decision maker

ne	maximum number of ECs that can be opened

Decision variables

W_k	1, if EC k is opened; 0 otherwise, for all $k \in K$

PLN model 2 is formulated as the following Mixed Integer Linear Programming (MILP):

$$\begin{aligned} MIN &\sum_{i\in I}\sum_{j\in J} tcmc_{ij}\cdot dmc_{ij}\cdot X_{ij} + \sum_{i\in I}\sum_{k\in K} tcme_{ik}\cdot dme_{ik}\cdot Y_{ik} \\ &+ \sum_{k\in K}\sum_{j\in J} tcem_{kj}\cdot dem_{kj}\cdot Z_{kj} + \sum_{i\in I}\sum_{j\in J} vmc_{ij}\cdot NVMC_{ij} \\ &+ \sum_{i\in I}\sum_{k\in K} vme_{ik}\cdot NVME_{ik} + \sum_{k\in K}\sum_{j\in J} vem_{kj}\cdot NVEM_{kj} + \sum_{k\in K} cec_k\cdot W_k \end{aligned} \tag{12}$$

subject to

$$\sum_{i\in I} Y_{ik} - \sum_{j\in J} Z_{kj} = 0, \quad \text{all } k \in K \tag{13}$$

$$\sum_{j\in J} X_{ij} + \sum_{k\in K} Y_{ik} = s_i, \quad \text{all } i \in I \tag{14}$$

$$\sum_{i\in I} X_{ij} + \sum_{k\in K} Z_{kj} = \sum_{i\in I} s_i\cdot r_{ij}, \quad \text{all } j \in J \tag{15}$$

$$X_{ij} = s_i\cdot r_{ij} (\text{if } s_i\cdot r_{ij} \geqslant cc), \quad \text{all } i \in I, j \in J \tag{16}$$

$$\sum_{i\in I} Y_{ik} - cap_k\cdot W_k \leqslant 0, \quad \text{all } k \in K \tag{17}$$

$$\sum_{k\in K} W_k \leqslant ne \tag{18}$$

$$X_{ij} - cc\cdot NVMC_{ij} \leqslant 0, \quad \text{all } i \in I, j \in J(i\neq j) \tag{19}$$

Table 5
Annual mail quantity collected at MPC i (s_i) and mail quantity delivered to MPC j (a_j).

MPC	s_i (pieces)	a_j (pieces)
1	10,700,000	38,399,000
2	350,600,000	175,806,900
3	46,300,000	97,798,000
4	79,200,000	128,284,600
5	69,900,000	103,508,200
6	1,335,800,000	551,064,600
7	88,100,000	190,407,500
8	280,100,000	269,865,700
9	604,400,000	363,373,500
10	77,700,000	266,540,500
11	66,300,000	126,647,000
12	13,300,000	56,785,500
13	12,100,000	41,456,100
14	246,500,000	205,853,400
15	9,600,000	83,594,500
16	24,000,000	87,056,300
17	26,600,000	67,802,600
18	97,700,000	232,121,600
19	29,300,000	83,313,200
20	12,300,000	64,352,700
21	22,700,000	104,857,800
22	21,700,000	73,464,400
23	24,700,000	87,170,300
24	11,000,000	61,076,100
Sum	3,560,600,000	3,560,600,000

Table 6
Computational results of Model 1.

Number of variables	Number of constraints	Objective function value (₩)	Number of vehicles	
			MPC–MPC	MPC–EC
1249	1250	43,256,691,750	11,182	38

Fig. 4. Optimal network design using Model 1.

$$NVMC_{ij} = 0, \quad \text{all } i \in I, j \in J(i = j) \tag{20}$$

$$Y_{ik} - cc \cdot NVME_{ik} \leqslant 0, \quad \text{all } i \in I, k \in K \tag{21}$$

$$Z_{kj} - cc \cdot NVEM_{kj} \leqslant 0, \quad \text{all } k \in K, j \in J \tag{22}$$

$$X_{ij}, Y_{ik}, Z_{kj}, NVMC_{ij}, NVME_{ik}, NVEM_{kj}$$
$$N : \text{Non} - \text{negative integer}, \quad \text{all } i \in I, j \in J, k \in K \tag{23}$$

$$W_k \in \{0, 1\}, \quad \text{all } k \in K \tag{24}$$

The objective function (12) minimizes the sum of the transportation costs, the fixed costs for using the vehicles, and the fixed costs of opening ECs. Constraints (13)-(16) and Eqs. (19)-(23) are the same as in Model 1. In Model 2, we use constraint (17) for enforcing that the total mail transported to an opened EC cannot exceed its capacity. Constraint (18) specifies that the number of opened ECs cannot exceed the maximum number of opened ECs. Especially, this constraint enables the decision maker to select how many ECs to open. Constraint (24) stipulates that the variables are binary (the ECs are either open or closed).

Table 7
Transported mail quantities (pieces) in Model 1.

i	j																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	EC
1	1,102,100	513,600	–	267,500	438,700	984,400	267,500	706,200	642,000	663,400	363,800	–	–	492,200	–	445,900	2,043,700	716,900	–	–	–	434,700	–	617,400	–
2	3,506,000	14,024,000	9,816,800	14,374,600	12,972,200	38,916,600	18,932,400	35,761,200	29,450,400	27,346,800	14,024,000	4,557,800	4,207,200	22,789,000	3,856,600	9,466,200	6,661,400	28,398,600	19,283,000	5,609,600	8,414,400	6,661,400	6,661,400	4,908,400	–
3	–	972,300	20,372,000	509,300	879,700	2,222,400	787,100	1,620,500	1,666,800	1,064,900	509,300	4,583,700	–	1,203,800	4,861,500	–	277,800	1,111,200	1,805,700	–	370,400	370,400	277,800	–	833,400
4	554,400	1,980,000	871,200	16,473,600	2,217,600	6,019,200	5,068,800	3,722,400	4,039,200	3,088,800	1,504,800	475,200	6,811,200	2,376,000	316,800	3,009,600	1,108,800	2,296,800	792,000	2,059,200	2,534,400	792,000	950,400	10,137,600	–
5	908,700	2,306,700	2,097,000	2,865,900	9,646,200	4,613,400	3,075,600	4,613,400	2,516,400	2,516,400	2,516,400	1,328,100	838,800	2,236,800	908,700	1,677,600	1,747,500	3,425,100	2,865,900	1,048,500	2,236,800	8,108,400	5,312,400	489,300	–
6	9,350,600	66,790,000	25,380,200	45,417,200	33,395,000	399,404,200	56,103,600	90,834,400	92,170,200	101,520,800	44,081,400	12,022,200	9,350,600	65,454,200	8,014,800	26,716,000	20,037,000	109,535,600	24,044,400	10,686,400	24,044,400	24,044,400	21,372,800	16,029,600	–
7	704,800	2,202,500	1,762,000	5,638,400	2,290,600	3,612,100	15,241,300	3,700,200	2,466,800	2,995,400	1,850,100	1,145,300	1,233,400	3,171,600	704,800	12,598,300	1,145,300	4,493,100	1,409,600	4,405,000	10,924,400	881,000	1,233,400	2,290,600	–
8	3,921,400	19,887,100	7,842,800	3,361,200	10,363,700	22,688,100	11,764,200	39,214,000	19,326,900	16,245,800	14,565,200	3,921,400	7,282,600	22,408,000	11,204,000	5,041,800	6,442,300	17,646,300	3,081,100	6,722,400	4,481,600	8,122,900	6,722,400	7,842,800	–
9	9,670,400	29,615,600	10,274,800	12,692,400	4,230,800	4,835,200	40,494,800	25,989,200	160,770,400	62,857,600	15,110,000	9,670,400	4,230,800	16,923,200	41,099,200	11,483,600	10,274,800	23,571,600	12,692,400	21,154,000	33,846,400	9,066,000	27,802,400	6,044,000	–
10	621,600	5,128,200	1,398,600	2,408,700	1,787,100	13,519,800	2,253,300	7,148,400	8,080,800	6,449,100	5,205,900	621,600	388,500	6,293,700	466,200	1,087,800	1,709,400	6,526,800	1,320,900	466,200	1,010,100	1,243,200	1,320,900	1,243,200	–
11	530,400	4,641,000	795,600	994,500	1,392,300	5,105,100	1,193,400	7,558,200	3,447,600	11,403,600	2,784,600	397,800	397,800	10,276,500	397,800	596,700	1,591,200	7,226,700	928,200	464,100	1,060,800	1,657,500	994,500	464,100	–
12	–	–	532,000	–	–	–	150,700	–	–	–	–	11,557,700	–	–	345,800	–	–	–	–	458,800	255,000	–	–	––	–
13	–	411,400	–	2,504,700	302,500	822,800	532,400	629,200	592,900	399,300	–	–	556,600	459,800	–	326,700	934,600	459,800	–	–	100,500	–	247,500	2,819,300	–
14	2,218,500	13,557,500	6,409,000	9,367,000	8,381,000	20,706,000	11,339,000	26,868,500	20,952,500	14,790,000	13,064,500	2,958,000	1,725,500	38,207,500	1,972,000	4,930,000	4,683,500	16,762,000	7,148,500	2,465,000	4,683,500	4,683,500	5,423,000	3,204,500	–
15	–	–	940,800	–	–	–	–	–	–	–	–	922,400	–	–	7,296,000	–	–	–	440,800	––	–	–	–	–	–
16	688,000	504,000	360,000	1,032,000	576,000	1,176,000	8,736,000	816,000	816,000	624,000	336,000	–	264,000	648,000	–	2,688,000	–	600,000	288,000	936,000	1,464,000	–	264,000	840,000	344,000
17	3,085,600	1,303,400	22,000	585,200	585,200	2,527,000	558,600	2,207,800	1,223,600	2,340,800	1,409,800	–	292,600	1,383,200	–	345,800	3,431,400	2,553,600	319,200	–	478,800	319,200	851,200	266,000	510,000
18	879,300	8,011,400	2,735,600	3,712,600	3,419,500	16,120,500	4,201,100	10,160,800	8,597,600	7,718,300	4,494,200	1,074,700	977,000	6,448,200	879,300	2,051,700	2,833,300	1,660,900	2,637,900	781,600	1,856,300	2,442,500	2,637,900	1,367,800	–
19	–	1,201,300	4,453,600	761,800	2,578,400	1,904,500	937,600	2,314,700	1,523,600	1,113,400	996,200	996,200	263,700	1,084,100	556,700	498,100	556,700	1,259,900	2,812,800	791,100	615,300	791,100	703,200	351,600	234,400
20	–	282,900	385,800	910,200	307,500	676,500	1,586,700	1,008,600	947,100	–	381,300	270,900	–	664,200	482,300	799,500	–	381,300	–	1,648,200	1,365,300	–	–	201,700	–
21	–	385,900	510,000	1,044,200	385,900	658,300	5,448,000	522,100	635,600	454,000	340,500	–	642,700	408,600	232,000	1,997,600	–	499,400	363,200	3,949,800	3,927,100	–	–	295,100	–
22	–	889,700	368,900	585,900	3,645,600	1,540,700	477,400	1,996,400	1,150,100	1,041,600	1,670,900	282,100	–	1,085,000	–	325,500	520,800	1,128,400	477,400	–	282,100	1,953,000	1,302,000	–	976,500
23	–	864,500	469,300	765,700	3,260,400	2,000,700	741,000	1,704,300	1,309,100	1,358,500	938,600	–	321,100	1,210,300	–	419,900	1,803,100	1,333,800	518,700	–	642,200	1,383,200	2,494,700	321,100	839,800
24	657,200	–	–	1,947,000	374,000	726,000	517,000	572,000	847,000	–	–	–	1,672,000	484,000	–	550,000	–	341,000	–	706,800	264,000	–	–	1,342,000	–
EC	–	333,900	–	65,000	78,300	285,100	–	197,200	200,900	548,000	499,500	–	–	145,500	–	–	–	192,800	83,500	–	–	510,000	598,400	–	

Table 8
Number of vehicles used in Model 1.

i	*j* 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	EC
1	–	3	–	2	2	4	2	3	3	3	2	–	–	2	–	2	9	3	–	–	–	2	–	3	–
2	14	–	39	57	51	153	75	141	116	108	55	18	17	90	16	38	27	112	76	22	33	27	27	20	–
3	–	4	–	2	4	9	4	7	7	5	2	18	–	5	20	–	2	5	8	–	2	2	2	–	4
4	3	8	4	–	9	24	20	15	16	13	6	2	27	10	2	12	5	10	4	9	10	4	4	40	–
5	4	10	9	12	–	19	13	19	10	10	10	6	4	9	4	7	7	14	12	5	9	32	21	2	–
6	37	262	100	179	131	–	221	357	362	399	173	48	37	257	32	105	79	430	95	42	95	95	84	63	–
7	3	9	7	23	9	15	–	15	10	12	8	5	5	13	3	50	5	18	6	18	43	4	5	9	–
8	16	78	31	14	41	89	47	–	76	64	58	16	29	88	44	20	26	70	13	27	18	32	27	31	–
9	38	117	41	50	17	19	159	102	–	247	60	38	17	67	162	46	41	93	50	83	133	36	110	24	–
10	3	21	6	10	8	54	9	29	32	–	21	3	2	25	2	5	7	26	6	2	4	5	6	5	–
11	3	19	4	4	6	21	5	30	14	45	–	2	2	41	2	3	7	29	4	2	5	7	4	2	–
12	–	–	3	–	–	–	1	–	–	–	–	–	–	–	2	–	–	–	–	2	1	–	–	–	–
13	–	2	–	10	2	4	3	3	3	2	–	–	–	2	–	2	4	2	–	–	1	–	1	12	–
14	9	54	26	37	33	82	45	106	83	58	52	12	7	–	8	20	19	66	29	10	19	19	22	13	–
15	–	–	4	–	–	–	–	–	–	–	–	4	–	–	–	–	–	–	2	–	–	–	–	–	–
16	3	2	2	5	3	5	35	4	4	3	2	–	2	3	–	–	–	3	2	4	6	–	2	4	2
17	13	6	1	3	3	10	3	9	5	10	6	–	2	6	-	2	–	11	2	–	2	2	4	2	2
18	4	32	11	15	14	64	17	40	34	31	18	5	4	26	4	9	12	–	11	4	8	10	11	6	–
19	–	5	18	3	11	8	4	10	6	5	4	4	2	5	3	2	3	5	–	4	3	4	3	2	1
20	–	2	2	4	2	3	7	4	4	–	2	2	–	3	2	4	–	2	–	–	6	–	–	1	–
21	–	2	2	5	2	3	22	3	3	2	2	–	3	2	1	8	–	2	2	16	–	–	–	2	–
22	–	4	2	3	15	7	2	8	5	5	7	2	–	5	–	2	3	5	2	–	2	–	6	–	4
23	–	4	2	4	13	8	3	7	6	6	4	–	2	5	–	2	8	6	3	–	3	6	–	2	4
24	3	–	–	8	2	3	3	3	4	–	–	–	7	2	–	3	–	2	–	3	2	–	–	–	–
EC	–	2	–	1	1	2	–	1	1	3	2	–	–	1	–	–	–	1	1	–	–	2	3	–	11,220

Table 9
Real data in 2008 and 2009 and forecast data from 2010 through 2015.

Year	%	Total mail quantities (pieces)
2008	–	3,560,600,000
2009	–	3,485,400,000
2010	−1.3	3,419,500,000
2011	−1.1	3,374,900,000
2012	−0.9	3,337,900,000
2013	−0.8	3,307,700,000
2014	−0.6	3,281,100,000
2015	−1.9	3,261,400,000

Table 10
Comparison results from 2008 through 2015.

Year	Objective function value (₩)	Number of vehicles	
		MPC–MPC	MPC–EC
2008	43,256,691,750	11,182	38
2009	42,343,558,090	10,949	36
2010	41,526,285,180	10,736	32
2011	40,987,374,510	10,601	34
2012	40,542,025,870	10,495	32
2013	40,178,522,100	10,406	33
2014	39,855,317,940	10,322	33
2015	39,613,940,560	10,264	34

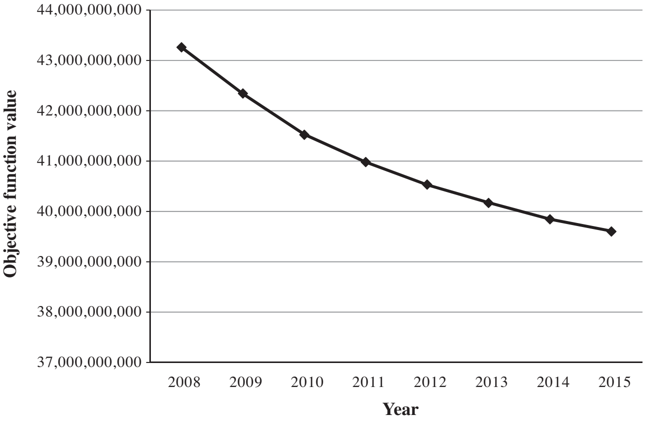

Fig. 5. Comparison of the objective function values from 2008 through 2015.

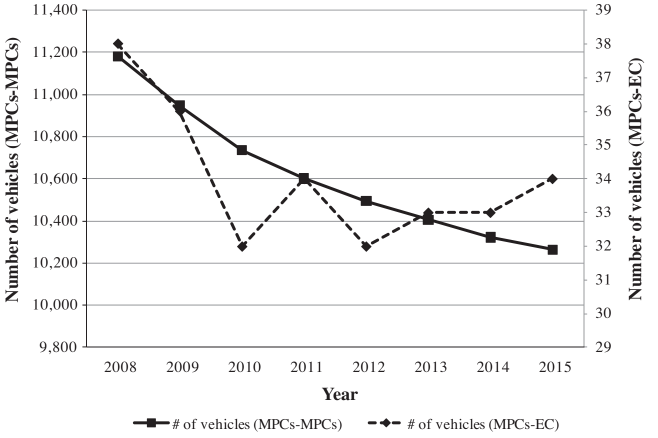

Fig. 6. Comparison of the number of vehicles traveling MPCs–MPCs and MPCs–EC.

4. Computational experiments

We use the real distance data between two points under vehicular transportation. The real distance is obtained by using a navigation device. Also, we use the actual mail-received data, mail-delivered data, and transportation rate data from 2008 with a slight modification because of the confidentiality of the information.

The distance data between pairs of MPCs and between MPCs and the EC and the transportation rate data are shown in Tables 2–4, respectively. In Table 2, the distance matrix between pairs of MPCs is an asymmetric matrix. Actually, the transportation

Table 11
Distance matrix between the MPCs and ECs (km).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
EC 1	219	145	115	126	0	129	199	137	132	110	104	145	135	119	168	205	124	150	37	146	181	63	42	186
EC 2	162	26	230	212	130	2	287	26	11	19	29	261	178	19	282	281	80	22	153	261	273	71	101	257
EC 3	178	14	234	227	133	18	302	8	9	29	33	265	193	18	286	296	95	29	157	266	288	74	108	272
EC 4	432	313	0	212	141	285	242	308	289	261	255	87	292	274	85	308	321	314	101	158	210	205	195	287
EC 5	437	412	244	103	268	373	0	404	385	363	357	165	198	370	324	71	317	393	253	95	49	307	264	108

Table 12
Six scenarios for the decision maker.

Scenarios	Number of opening ECs	Location of opening ECs		
		Current	Capital area	South
1	1	1	2	0
2	1	1	2	2
3	2	1 (fixed)	2	0
4	2	1 (fixed)	2	2
5	3	1	2	0
6	3	1 (fixed)	2 (⩾1)	2 (⩾1)

distance is different from *i* to *j* and from *j* to *i* because there are limitations, such as one-way streets along the route. Table 3 shows the actual transportation distance matrix between EC and MPC. This matrix is a symmetric matrix unlike the matrix of MPCs. Table 4 shows the forecasted transportation rate based on historical data from each sending MPC to each receiving MPC. The sum of each row is one. The value of each cell is derived by dividing the amount sent from one MPC into the total amount sent from all of the MPCs in the same row. The annual mail quantities collected at MPCs and the mail quantities to be delivered to MPCs are shown in Table 5. The EC capacity is set to half a billion because the EC can be exchanged at 500,000 mail items per hour, and operates for 4 h per day, 250 days per year. The mathematical models were coded and solved by *IBM ILOG OPL Development Studio* 5.5 with the *ILOG*

Table 13
Comparison of the results of the scenarios.

Scenarios	Objective function value (₩) (transportation cost + vehicle cost + EC opening cost)	Opened locations	Number of vehicles	
			MPCs–MPCs	MPCs–ECs
1	40,601,143,670 (34,454,143,670 + 5,147,000,000 + 1,000,000,000)	EC 2	10,267	27
2	40,600,936,190 (34,454,436,190 + 5,146,500,000 + 1,000,000,000)	EC 2	10,269	24
3	41,590,080,550 (34,439,580,550 + 5,150,500,000 + 2,000,000,000)	ECs 1 and 2	10,261	40
4	41,589,834,660 (34,439,834,660 + 5,150,000,000 + 2,000,000,000)	ECs 1 and 2	10,262	38
5	42,589,330,960 (34,439,330,960 + 5,150,000,000 + 3,000,000,000)	ECs 1, 2, and 3	10,259	41
6	42,570,901,590 (34,416,401,590 + 5,154,500,000 + 3,000,000,000)	ECs 1, 2, and 5	10,249	60

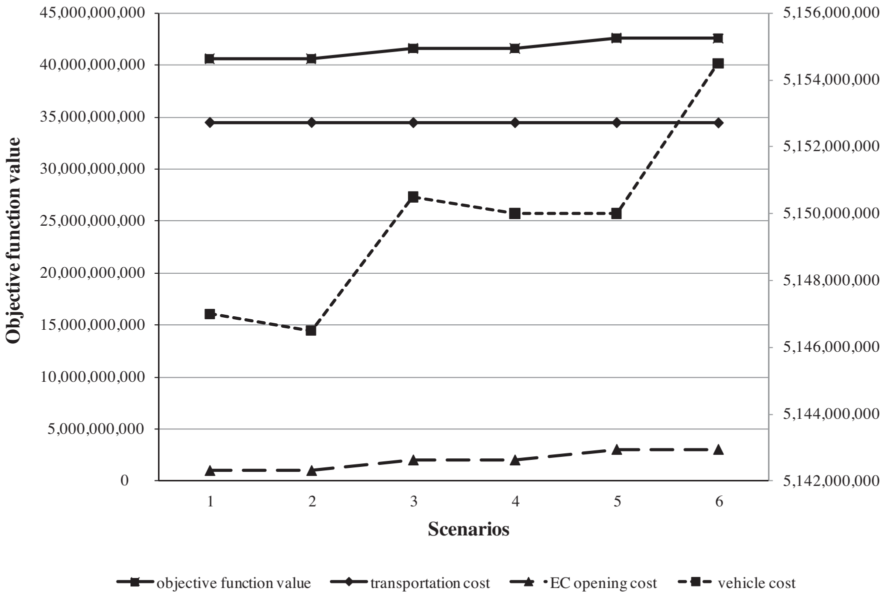

Fig. 7. Comparison of the objective function values of the scenarios.

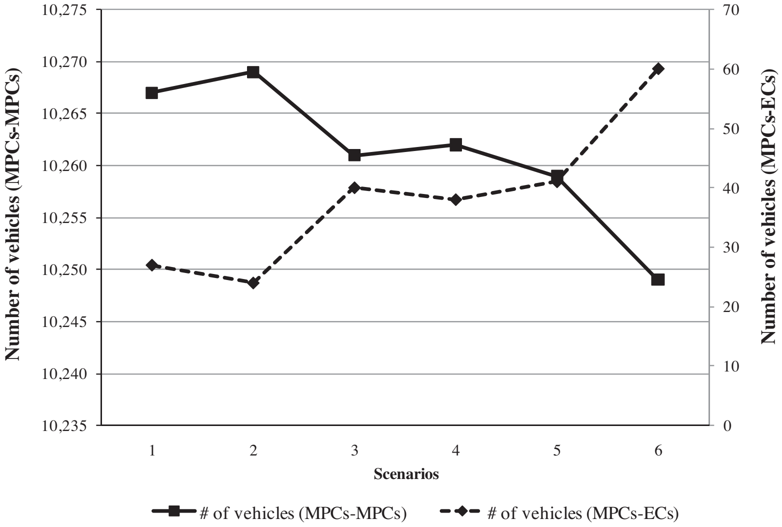

Fig. 8. Comparison of the number of vehicles traveling MPCs–MPCs and MPCs–EC.

CPLEX 11.0 engine (ILOG, 2009). The computational time was less than about 10 s using an Intel Core 2 2.66 GHz PC with 3 GB RAM on the Microsoft Windows XP operating system.

Table 6 shows the objective function value, the number of constraints, the number of variables, and the number of vehicles used in Model 1. The graphical configurations of the optimal network in Model 1 are shown in Fig. 4. Table 7 shows the transported mail quantities between pairs of points, and Table 8 shows the specific number of vehicles that are used in Model 1.

For applications to decision making in postal logistics network design, we experimented with various mail quantities in Model 1. The experimental data involved real mail quantities in 2009 and forecasted mail quantities, which were based on data for the preceding seven years; forecasts were performed for 2010 through 2015. Table 9 shows the results of the forecasting (Korea Post, 2010). Table 10 shows detailed results from 2008 through 2015. From Table 10, we ascertain that the number of vehicles between the MPCs and the EC is consistent, while the number of vehicles between the MPCs decreases according to the decreasing mail quantities. When mail quantities decrease, because the mail does not amount to a single vehicle's capacity, it is sent to the EC. Figs. 5 and 6 graphically illustrate the objective function value and the number of vehicles used.

In addition, to support the network decision maker, we generate 6 scenarios using Model 2. Table 11 shows the distance data between the MPCs and the potential ECs. EC 1 operates in the middle of Korea. In terms of the construction cost for the EC, we use a fixed cost that considers the EC's scale with respect to the mail volume, operation space, parking space, depreciation of buildings (50 years) and equipment (15 years) in the Korea Post technical report. The construction planning of ECs 2–5 is that ECs 2 and 3 will be located in the vicinity of the capital and ECs 4 and 5 will be located at the south of Korea. The detailed scenarios are shown in Table 12. Table 13 and Figs. 7 and 8 show a comparison of the results across the 6 scenarios.

In Table 13, with the results of scenarios 1 and 2, the current location of the EC is not the optimal location; however, this location is the best location considering the geographical location, operation strategy, and other various surrounding circumstances. If we add one more EC in the future, then EC 2, in the vicinity of the capital, is at the optimal location. In addition, if we add two more ECs in the vicinity of the capital and the south of Korea, respectively, then ECs 2 and 5 are at the optimal locations. For the location of an EC, we have to consider various elements for decision making, but the result of the scenario is important because the network design problem is the most important determinant in the service and cost aspects.

Fig. 7 shows the objective function value for each scenario. We ascertain that the objective function value is increased according to the increasing in the number of ECs used. In addition, the transportation cost and vehicle cost do not have an effect that is nearly as large as in the case of constructing the same EC, because the construction cost is very large. Fig. 8 shows the number of vehicles used between MPCs and between MPCs and ECs for each scenario. As a result, when the number of ECs increases, the number of vehicles used between the MPCs decreases and the number of vehicles used between MPCs and ECs increases. This approach can, in general, be applied to develop robust solutions in uncertain and dynamic decision situations.

5. Conclusions

This paper considered postal logistics network design with realistic restrictions. We developed mathematical models for hybrid hub-and-spoke postal logistics network designs by considering the transportation network and vehicle operations with realistic restrictions. We considered 24 MPCs and one or more ECs, and we used real data (e.g., distance data, mail-received data, mail-delivered data, and transportation rate data) by simultaneously considering the locations and allocations. The mathematical models have been coded and solved by ILOG OPL Development Studio 5.5 with the ILOG CPLEX 11.0 engine. The computational times of all of the models were less than about 10 s. The computational experiments demonstrate the usefulness of the mathematical models that were developed. Moreover, the proposed scenarios are very useful in decision making for postal logistics network designers and operators. The network problem occurs in postal logistics is more complex and diverse than that for general logistics. Moreover, the amount of data is enormous which makes the decision makers difficult to design the network. It was impossible to compute the restrictions on vehicle capacity, assignment of vehicles in accordance with transportation rates, and delivery quantities to each EC (Exchange Center) manually. If one uses our model for postal logistics, one can easily design the optimal network for the existing facilities. Moreover, one can use this model to design the optimal network to minimize total costs by observing facility capacities and various practical restrictions when new ECs are being constructed.

In addition, the models can be applied to the multi-item supply chain and to parcel delivery service companies and, in general, can also be applied to develop robust solutions in uncertain and dynamic decision situations. Further studies can explore several different directions. First, we may develop an integrated mathematical model that considers D&PSs and all types of mail. Second, we can develop a user-friendly decision support system that applies the developed mathematical models. Third, we can develop a simulation model by changing some parameters into random variables. Fourth, we may consider other objective functions, such as service time, service level, and the mail processing rate.

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