Appendices

Proof of Lemma 1:

Lemma 1 $z_j = \sum_{q \in Q} z_{jq} q$, and $\sum_{q \in Q} z_{jq} = y_j$, $\forall j \in H$.

Proof: When hub j is opened, $y_j = 1$. When z_j is restricted to one and only one element of set Q, we have $\sum_{q \in Q} z_{jq} = 1 = y_j$. Suppose that $z_j = \delta$. From the definition of z_{jq}, we have $z_j = \delta = z_{j\delta}\delta = \sum_{q \in Q} z_{jq} q$.

When hub j is closed, $y_j = 0$. It is trivial that $z_j = 0$ and $z_{jq} = 0, \forall q \in Q$. Obviously, $z_j = 0 = \sum_{q \in Q} z_{jq} q$, and $\sum_{q \in Q} z_{jq} = 0 = y_j$. □

Table A1: The 19 districts, their population density and per capita GDP

Node	District	Pupulation Density	Per Capital GDP
1	Pudong	4468	19098
2	Huangpu	33083	33791
3	Xuhui	20547	15742
4	Changning	18418	17938
5	Jing'an	32795	41726
6	Putuo	23629	8997
7	Zhabei	28958	12378
8	Hongkou	35757	13327
9	Yangpu	21806	16037
10	Baoshan	6830	11087
11	Minhang	7414	7386
12	Jiading	3353	11101
13	Jinshan	1331	14891
14	Songjiang	2867	8904
15	Qingpu	1787	11090
16	Fengxian	1679	9284
17	Chongming	588	5593

Table A2: The shortest distance matrix between the districts

Districts	Pudong	Huangpu	Luwan	Xuhui	Changning	Jing'an	Putuo	Zhabei	Hongkou	Yangpu	Baoshan	Minhang	Jiading	Jinshan	Songjiang	Qingpu	Nanhui	Fengxian	Chongming
Pudong	0	6.3	7.6	12.4	12.4	10.3	16.4	9.8	6.5	6.9	24.3	22.7	36.0	66.9	41.6	43.1	35.8	40.6	67.3
Huangpu	6.3	0	2.3	7.0	6.1	3.9	10.1	3.4	4.7	5.7	21.2	17.3	29.7	65.1	36.3	37.1	42.2	39.7	63.0
Luwan	7.6	2.3	0	5.0	5.2	3.3	9.3	3.7	7.1	8.1	23.4	15.3	29.5	63.1	34.2	35.7	42.7	37.4	63.4
Xuhui	12.4	7.0	5.0	0	4.0	4.7	8.8	7.8	12.0	13.3	28.0	10.2	29.9	57.3	30.0	32.1	43.6	34.8	67.8
Changning	12.4	6.1	5.2	4.0	0	2.3	5.0	4.8	10.0	11.3	25.1	14.3	26.1	61.4	32.2	31.6	46.5	38.9	64.7
Jing'an	10.3	3.9	3.3	4.7	2.3	0	6.1	2.6	7.4	8.5	22.7	15.0	27.3	62.8	33.9	33.8	44.8	38.8	62.7
Putuo	16.4	10.1	9.3	8.8	5.0	6.1	0	7.1	12.3	14.2	24.3	17.7	21.3	63.5	34.1	33.2	50.8	41.7	62.8
Zhabei	9.8	3.4	3.7	7.8	4.8	2.6	7.1	0	5.2	7.0	20.6	18.0	26.0	65.8	37.0	36.6	45.4	40.9	60.6
Hongkou	6.5	4.7	7.1	12.0	10.0	7.4	12.3	5.2	0	2.4	17.9	22.3	29.8	70.1	41.3	41.5	42.4	44.5	60.8
Yangpu	6.9	5.7	8.1	13.3	11.3	8.5	14.2	7.0	2.4	0	18.9	23.6	31.9	70.8	42.5	42.8	40.3	44.5	61.9
Baoshan	24.3	21.2	23.4	28.0	25.1	22.7	24.3	20.6	17.9	18.9	0	38.3	22.9	86.2	57.2	53.3	54.8	60.8	43.8
Minhang	22.7	17.3	15.3	10.2	14.3	15.0	17.7	18.0	22.3	23.6	38.3	0	34.6	47.7	19.7	29.1	44.6	24.7	78.1
Jiading	36.0	29.7	29.5	29.9	26.1	27.3	21.3	26.0	29.8	31.9	22.9	34.6	0	78.0	43.1	32.9	71.6	58.1	54.3
Jinshan	66.9	65.1	63.1	57.3	61.4	62.8	63.5	65.8	70.1	70.8	86.2	47.7	78.0	0	38.8	57.0	60.5	27.7	125.7
Songjiang	41.6	36.3	34.2	30.0	32.2	33.9	34.1	37.0	41.3	42.5	57.2	19.7	43.1	38.8	0	19.6	59.4	34.7	96.0
Qingpu	43.1	37.1	35.7	32.1	31.6	33.8	33.2	36.6	41.5	42.8	53.3	29.1	32.9	57.0	19.6	0	73.1	52.6	86.3
Nanhui	35.8	42.2	42.7	43.6	46.5	44.8	50.8	45.4	42.4	40.3	54.8	44.6	71.6	60.5	59.4	73.1	0	34.5	99.2
Fengxian	40.6	39.7	37.4	34.8	38.9	38.8	41.7	40.9	44.5	44.5	60.8	24.7	58.1	27.7	34.7	52.6	34.5	0	100.7
Chongming	67.3	63.0	63.4	67.8	64.7	62.7	62.8	60.6	60.8	61.9	43.8	78.1	54.3	125.7	96.0	86.3	99.2	100.7	0