OR 7310 – LOGISTICS WAREHOUSING AND SCHEDULING

Telecommunication Design Network Problem

Project Report

Team Members

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Introduction

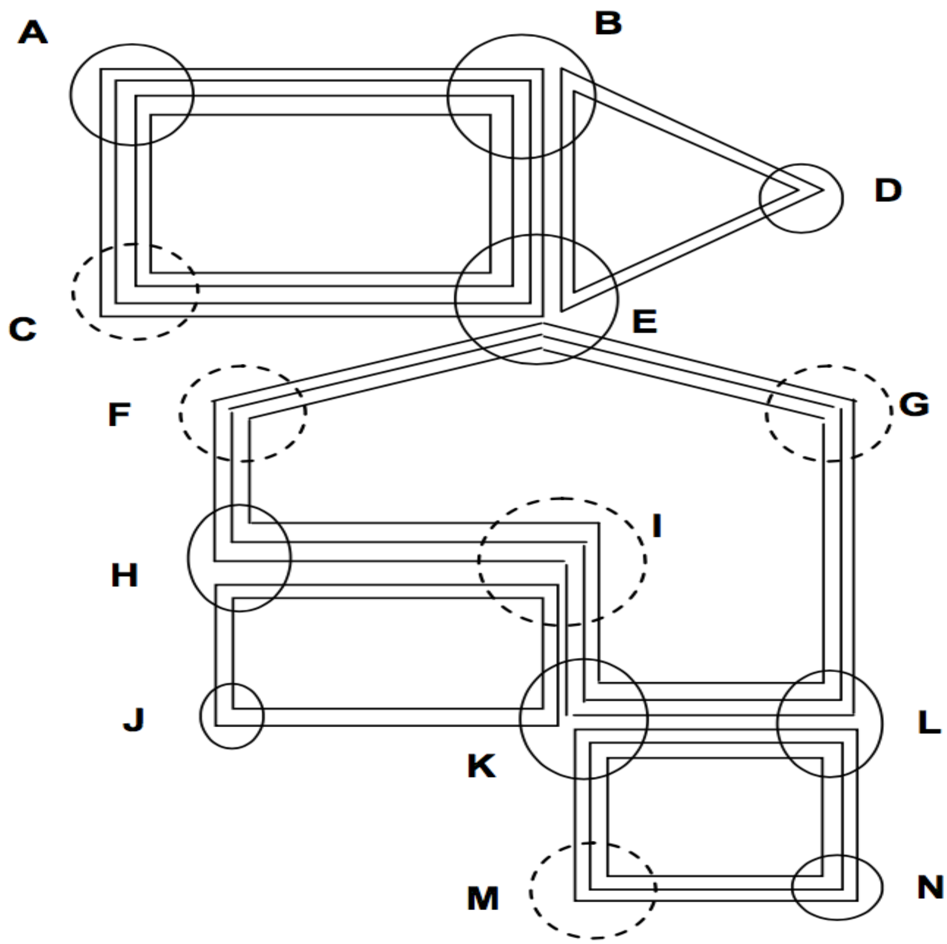
The problem at hand is a real-world NP hard problem combining facility location and routing networks. The company is building two networks, A Caldata network and a Barry network. Both networks are made up of hubs which represent the locations. These hubs are connected to one another by arcs.

Data can switch from one ring to another only if there is a BBDX installed. These BBDX's are fixed (represented by the solid circles). To allow data to enter or leave a ring at a hub the ring must have an add-drop multiplexer (ADM) installed at the hub. This restriction applies not only to data entering or leaving the network, but also to data switching from one ring to the other. The cost of an ADM is 1,000,000 per year including the operation and installation cost.

The main objective of this project is to minimize the number of ADMs installed by deciding the location of the hubs and the rings on which to install the ADMs so that they satisfy the capacity and flow constraints of the network.

Caldata Network

The given Caldata network is shown in the figure below.



There are 14 hubs labeled A through N. The flow capacity of each arc in this network is 24000 units. Flow exists in both direction in the arcs.

As data flows from one hub to another in this network, it will often have to switch from one ring to another. And ring-switching is only possible at hubs that have a BBDX installed. In addition, data can only enter or leave a ring at a hub if the ring has an ADM installed at that hub. Since the locations of the BBDX is given to us, the only thing to figure out are the locations of the ADMs to minimize total cost of the project.

Solving the Caldata Network

To solve the caldata network problem, we decide to split the network into 2 parts. Both parts have a hub in common. In our case decide to split the network into part 1- ring ABCED & ring BED and part 2- ring EFHILG, ring HIKJ & ring KLMN.

The hub common to both parts is hub E. So, if there is a flow of data from (let's say) A to H, then the flow is split into two, from A to E and then E to H. The number ADMs will remain the same if we solve this problem in one part because the demand at the hubs will remain the same. However, the cost will change because we solve it separately and there will be change in cost at each location.

<u>PART 1 – Rings ABED and Rings BED</u>

```
Cycles: 2
set NODES[ABEC] := A B E C;
set NODES[BDE] := B D E;

rings [*] :=
ABEC  4
BDE  2
;

Hubs: 5
set HUB_NODES := A B E C D;

set RING_NODES :=
ABEC_A_1   ABEC_B_1   ABEC_E_1   ABEC_C_1   BDE_B_1   BDE_E_1
ABEC_A_2   ABEC_B_2   ABEC_E_2   ABEC_C_2   BDE_B_2   BDE_E_2
ABEC_A_3   ABEC_B_3   ABEC_E_3   ABEC_C_3   BDE_D_1
ABEC_A_4   ABEC_B_4   ABEC_E_4   ABEC_C_4   BDE_D_2;

bbdx [*] :=
A  1
B  1
C  0
D  1
E  1
;

Commodities: 12
Type 0 arcs: 22
Type 1 arcs: 22
```

Type 2 arcs: 44
Type 3 arcs: 74
CPLEX 12.8.0.0: optimal integer solution; objective 14512000
132713 MIP simplex iterations
1039 branch-and-bound nodes
adm [*] :=
ABEC_A_1 1   ABEC_B_1 1   ABEC_C_1 0   ABEC_E_1 1   BDE_B_1 0   BDE_E_1 0
ABEC_A_2 0   ABEC_B_2 1   ABEC_C_2 1   ABEC_E_2 1   BDE_B_2 1   BDE_E_2 1
ABEC_A_3 1   ABEC_B_3 1   ABEC_C_3 0   ABEC_E_3 0   BDE_D_1 0
ABEC_A_4 1   ABEC_B_4 0   ABEC_C_4 0   ABEC_E_4 1   BDE_D_2 1
;

The cost of Part 1 is 14512000

PART 2- Rings EFHILG, HIKJ & KLMN

Cycles: 3
set NODES[EGLKIHF] := E G L K I H F;
set NODES[HIKJ] := H I K J;
set NODES[KLNM] := K L N M;

rings [*] :=
EGLKIHF 3
HIKJ 2
KLNM 3
;

Hubs: 10
set HUB_NODES := E G L K I H F J N M;

set RING_NODES :=
EGLKIHF_E_1   EGLKIHF_K_1   EGLKIHF_F_1   HIKJ_J_1   KLNM_N_2
EGLKIHF_E_2   EGLKIHF_K_2   EGLKIHF_F_2   HIKJ_J_2   KLNM_N_3
EGLKIHF_E_3   EGLKIHF_K_3   EGLKIHF_F_3   KLNM_K_1   KLNM_M_1
EGLKIHF_G_1   EGLKIHF_I_1   HIKJ_H_1   KLNM_K_2   KLNM_M_2
EGLKIHF_G_2   EGLKIHF_I_2   HIKJ_H_2   KLNM_K_3   KLNM_M_3
EGLKIHF_G_3   EGLKIHF_I_3   HIKJ_I_1   KLNM_L_1
EGLKIHF_L_1   EGLKIHF_H_1   HIKJ_I_2   KLNM_L_2
EGLKIHF_L_2   EGLKIHF_H_2   HIKJ_K_1   KLNM_L_3
EGLKIHF_L_3   EGLKIHF_H_3   HIKJ_K_2   KLNM_N_1;

bbdx [*] :=
E 1
F 0
G 0
H 1
I 0

J 1
K 1
L 1
M 0
N 1
;

set EDGES :=
(E,G) (K,I) (F,E) (L,G) (H,I) (J,H) (L,N) (K,M)
(G,L) (I,H) (E,F) (K,L) (F,H) (H,J) (N,M) (N,L)
(L,K) (H,F) (G,E) (I,K) (K,J) (J,K) (M,K) (M,N);

Commodities: 19
Type 0 arcs: 41
Type 1 arcs: 41
Type 2 arcs: 82
Type 3 arcs: 120
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap; objective 24945000
478799 MIP simplex iterations
2943 branch-and-bound nodes
absmipgap = 2000, relmipgap = 8.01764e-05
adm [*] :=
EGLKIHF_E_1 1 EGLKIHF_H_1 0 EGLKIHF_L_1 0 HIKJ_K_1 1 KLNM_M_2 0
EGLKIHF_E_2 1 EGLKIHF_H_2 0 EGLKIHF_L_2 1 HIKJ_K_2 1 KLNM_M_3 0
EGLKIHF_E_3 1 EGLKIHF_H_3 1 EGLKIHF_L_3 0 KLNM_K_1 1 KLNM_N_1 1
EGLKIHF_F_1 1 EGLKIHF_I_1 0 HIKJ_H_1 1 KLNM_K_2 0 KLNM_N_2 1
EGLKIHF_F_2 0 EGLKIHF_I_2 0 HIKJ_H_2 0 KLNM_K_3 1 KLNM_N_3 1
EGLKIHF_F_3 0 EGLKIHF_I_3 0 HIKJ_I_1 0 KLNM_L_1 0
EGLKIHF_G_1 1 EGLKIHF_K_1 1 HIKJ_I_2 1 KLNM_L_2 1
EGLKIHF_G_2 0 EGLKIHF_K_2 0 HIKJ_J_1 1 KLNM_L_3 0
EGLKIHF_G_3 0 EGLKIHF_K_3 1 HIKJ_J_2 1 KLNM_M_1 1
;

The cost of Part 2 is 24945000.

Total Cost is 14512000 +24945000 = **39457000**

Running the caldata network as a whole

ampl: include caldata_toptest.run;
Cycles: 5
set NODES[ABEC] := A B E C;
set NODES[BDE] := B D E;
set NODES[EGLKIHF] := E G L K I H F;
set NODES[HIKJ] := H I K J;
set NODES[KLNM] := K L N M;

rings [*] :=

```
  ABEC  4
   BDE  2
EGLKIHF  3
  HIKJ  2
  KLNM  3
;

Hubs: 14
set HUB_NODES := A B E C D G L K I H F J N M;

set RING_NODES :=
ABEC_A_1     ABEC_C_2     EGLKIHF_G_2   EGLKIHF_H_3   KLNM_K_2
ABEC_A_2     ABEC_C_3     EGLKIHF_G_3   EGLKIHF_F_1   KLNM_K_3
ABEC_A_3     ABEC_C_4     EGLKIHF_L_1   EGLKIHF_F_2   KLNM_L_1
ABEC_A_4     BDE_B_1      EGLKIHF_L_2   EGLKIHF_F_3   KLNM_L_2
ABEC_B_1     BDE_B_2      EGLKIHF_L_3   HIKJ_H_1      KLNM_L_3
ABEC_B_2     BDE_D_1      EGLKIHF_K_1   HIKJ_H_2      KLNM_N_1
ABEC_B_3     BDE_D_2      EGLKIHF_K_2   HIKJ_I_1      KLNM_N_2
ABEC_B_4     BDE_E_1      EGLKIHF_K_3   HIKJ_I_2      KLNM_N_3
ABEC_E_1     BDE_E_2      EGLKIHF_I_1   HIKJ_K_1      KLNM_M_1
ABEC_E_2     EGLKIHF_E_1   EGLKIHF_I_2   HIKJ_K_2      KLNM_M_2
ABEC_E_3     EGLKIHF_E_2   EGLKIHF_I_3   HIKJ_J_1      KLNM_M_3
ABEC_E_4     EGLKIHF_E_3   EGLKIHF_H_1   HIKJ_J_2
ABEC_C_1     EGLKIHF_G_1   EGLKIHF_H_2   KLNM_K_1;

bbdx [*] :=
A  1
B  1
C  0
D  1
E  1
F  0
G  0
H  1
I  0
J  1
K  1
L  1
M  0
N  1
;

Commodities: 33
Type 0 arcs: 63
Type 1 arcs: 63
Type 2 arcs: 126
Type 3 arcs: 230
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap; objective 37731000
```

```
9441812 MIP simplex iterations
65595 branch-and-bound nodes
absmipgap = 3750.78, relmipgap = 9.94085e-05
adm [*] :=
  ABEC_A_1 1     ABEC_E_2 0   EGLKIHF_F_2 0   EGLKIHF_K_3 1     KLNM_K_2 0
  ABEC_A_2 1     ABEC_E_3 1   EGLKIHF_F_3 0   EGLKIHF_L_1 0     KLNM_K_3 1
  ABEC_A_3 0     ABEC_E_4 1   EGLKIHF_G_1 1   EGLKIHF_L_2 1     KLNM_L_1 0
  ABEC_A_4 1      BDE_B_1 1   EGLKIHF_G_2 0   EGLKIHF_L_3 0     KLNM_L_2 1
  ABEC_B_1 0      BDE_B_2 0   EGLKIHF_G_3 0      HIKJ_H_1 0     KLNM_L_3 0
  ABEC_B_2 1      BDE_D_1 1   EGLKIHF_H_1 1      HIKJ_H_2 1     KLNM_M_1 1
  ABEC_B_3 1      BDE_D_2 0   EGLKIHF_H_2 0      HIKJ_I_1 1     KLNM_M_2 0
  ABEC_B_4 1      BDE_E_1 1   EGLKIHF_H_3 0      HIKJ_I_2 0     KLNM_M_3 0
  ABEC_C_1 0      BDE_E_2 0   EGLKIHF_I_1 0      HIKJ_J_1 1     KLNM_N_1 1
  ABEC_C_2 0   EGLKIHF_E_1 1   EGLKIHF_I_2 0     HIKJ_J_2 1     KLNM_N_2 1
  ABEC_C_3 1   EGLKIHF_E_2 1   EGLKIHF_I_3 0     HIKJ_K_1 1     KLNM_N_3 1
  ABEC_C_4 0   EGLKIHF_E_3 1   EGLKIHF_K_1 0     HIKJ_K_2 0
  ABEC_E_1 1   EGLKIHF_F_1 1   EGLKIHF_K_2 0     KLNM_K_1 1
;
```

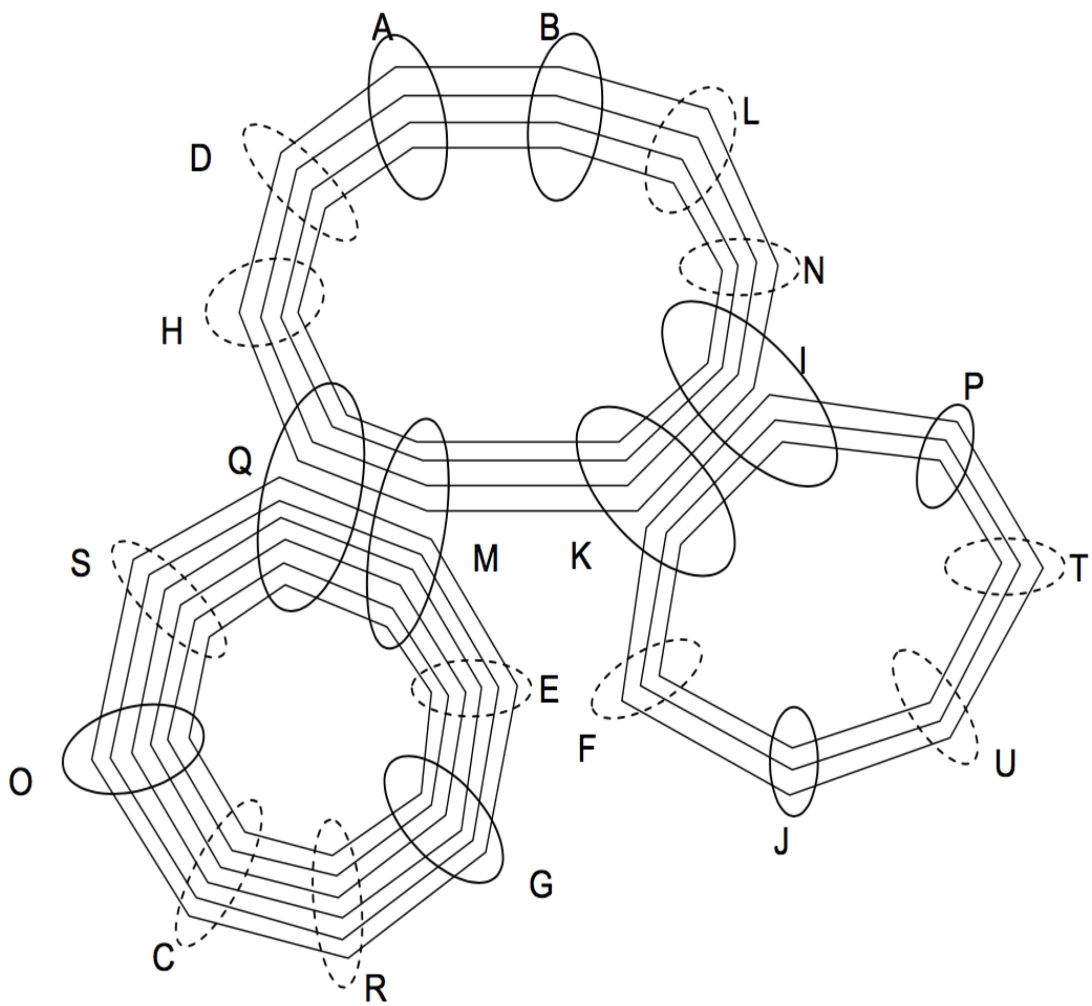
The total cost of running the network as a whole is **37731000**.

Optimality Gap

The optimality gap of the Caldata network through this method is calculated by $\frac{39457000-37731000}{37731000}$ which is equal to **0.0457 or 4.57%**

Barry Network

The barry network as shown below has 21 hubs. The fibers used in the barry network are twice as large as the caldata network. Hence, 48,000 units of data can flow through the arcs.



Solving the barry network problem

Lower Bound Solution.

To solve this, we use the same method of splitting the networks in two parts as employed in the caldata network. The common hubs in this network are Q, M, K, and I. since there is no flow from either hub Q to M or from hub M to Q and there is a flow from I to K, we decide to separate the ring QMEGRCOS. Since there is no flow between hub Q and M we can substitute this with a hub X. So if there is a flow from (let's say) B to G then the flow is split into B to X and X to G.

Part 1 includes ring XEGRCOS. Part 2 includes rings ABLNIKXHD and KIPTUJF.

PART 1 Ring XEGRCOS

Cycles: 1
set NODES[XEGRCOS] := X E G R C O S;
rings [*] :=
XEGRCOS 6
;
Hubs: 7
set HUB_NODES := X E G R C O S;
set RING_NODES :=
XEGRCOS_X_1 XEGRCOS_E_4 XEGRCOS_R_1 XEGRCOS_C_4 XEGRCOS_S_1
XEGRCOS_X_2 XEGRCOS_E_5 XEGRCOS_R_2 XEGRCOS_C_5 XEGRCOS_S_2
XEGRCOS_X_3 XEGRCOS_E_6 XEGRCOS_R_3 XEGRCOS_C_6 XEGRCOS_S_3
XEGRCOS_X_4 XEGRCOS_G_1 XEGRCOS_R_4 XEGRCOS_O_1 XEGRCOS_S_4
XEGRCOS_X_5 XEGRCOS_G_2 XEGRCOS_R_5 XEGRCOS_O_2 XEGRCOS_S_5
XEGRCOS_X_6 XEGRCOS_G_3 XEGRCOS_R_6 XEGRCOS_O_3 XEGRCOS_S_6
XEGRCOS_E_1 XEGRCOS_G_4 XEGRCOS_C_1 XEGRCOS_O_4
XEGRCOS_E_2 XEGRCOS_G_5 XEGRCOS_C_2 XEGRCOS_O_5
XEGRCOS_E_3 XEGRCOS_G_6 XEGRCOS_C_3 XEGRCOS_O_6;
bbdx [*] :=
C 0
E 0
G 1
O 1
R 0
S 0
X 1
;
set EDGES :=
(X,E) (G,R) (C,O) (S,X) (E,X) (R,G) (O,C)
(E,G) (R,C) (O,S) (X,S) (G,E) (C,R) (S,O);
Commodities: 22
Type 0 arcs: 42
Type 1 arcs: 42
Type 2 arcs: 84
Type 3 arcs: 90
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap; objective
26292820
1111004 MIP simplex iterations
6163 branch-and-bound nodes
absmipgap = 2060, relmipgap = 7.83484e-05

adm [*] :=
XEGRCOS_C_1 0 XEGRCOS_E_4 0 XEGRCOS_O_1 1 XEGRCOS_R_4 1 XEGRCOS_X_1 1
XEGRCOS_C_2 1 XEGRCOS_E_5 0 XEGRCOS_O_2 1 XEGRCOS_R_5 0 XEGRCOS_X_2 1
XEGRCOS_C_3 0 XEGRCOS_E_6 1 XEGRCOS_O_3 1 XEGRCOS_R_6 1 XEGRCOS_X_3 0
XEGRCOS_C_4 0 XEGRCOS_G_1 1 XEGRCOS_O_4 0 XEGRCOS_S_1 0 XEGRCOS_X_4 0
XEGRCOS_C_5 0 XEGRCOS_G_2 1 XEGRCOS_O_5 1 XEGRCOS_S_2 1 XEGRCOS_X_5 1
XEGRCOS_C_6 0 XEGRCOS_G_3 0 XEGRCOS_O_6 1 XEGRCOS_S_3 1 XEGRCOS_X_6 1
XEGRCOS_E_1 0 XEGRCOS_G_4 1 XEGRCOS_R_1 0 XEGRCOS_S_4 0
XEGRCOS_E_2 0 XEGRCOS_G_5 1 XEGRCOS_R_2 1 XEGRCOS_S_5 0

XEGRCOS_E_3 0 XEGRCOS_G_6 1 XEGRCOS_R_3 0 XEGRCOS_S_6 0
;

The cost of this ring is **26292820**

Part 2 Rings ABLNIKXHD and KIPTUJF.

Cycles: 2
set NODES[ABLNIKXHD] := A B L N I K X H D;
set NODES[IPTUJFK] := I P T U J F K;

rings [*] :=
ABLNIKXHD 4
IPTUJFK 3
;

Hubs: 14
set HUB_NODES := A B L N I K X H D P T U J F;

set RING_NODES :=
ABLNIKXHD_A_1 ABLNIKXHD_N_1 ABLNIKXHD_X_1 IPTUJFK_I_1 IPTUJFK_J_1
ABLNIKXHD_A_2 ABLNIKXHD_N_2 ABLNIKXHD_X_2 IPTUJFK_I_2 IPTUJFK_J_2
ABLNIKXHD_A_3 ABLNIKXHD_N_3 ABLNIKXHD_X_3 IPTUJFK_I_3 IPTUJFK_J_3
ABLNIKXHD_A_4 ABLNIKXHD_N_4 ABLNIKXHD_X_4 IPTUJFK_P_1 IPTUJFK_F_1
ABLNIKXHD_B_1 ABLNIKXHD_I_1 ABLNIKXHD_H_1 IPTUJFK_P_2 IPTUJFK_F_2
ABLNIKXHD_B_2 ABLNIKXHD_I_2 ABLNIKXHD_H_2 IPTUJFK_P_3 IPTUJFK_F_3
ABLNIKXHD_B_3 ABLNIKXHD_I_3 ABLNIKXHD_H_3 IPTUJFK_T_1 IPTUJFK_K_1
ABLNIKXHD_B_4 ABLNIKXHD_I_4 ABLNIKXHD_H_4 IPTUJFK_T_2 IPTUJFK_K_2
ABLNIKXHD_L_1 ABLNIKXHD_K_1 ABLNIKXHD_D_1 IPTUJFK_T_3 IPTUJFK_K_3
ABLNIKXHD_L_2 ABLNIKXHD_K_2 ABLNIKXHD_D_2 IPTUJFK_U_1
ABLNIKXHD_L_3 ABLNIKXHD_K_3 ABLNIKXHD_D_3 IPTUJFK_U_2
ABLNIKXHD_L_4 ABLNIKXHD_K_4 ABLNIKXHD_D_4 IPTUJFK_U_3;

bbdx [*] :=
A 1
B 1
D 0

```
F 0
H 0
I 1
J 1
K 1
L 0
N 0
P 1
T 0
U 0
X 1
;

set EDGES :=
(A,B)  (N,I)  (X,H)  (A,D)  (N,L)  (X,K)  (I,P)  (U,J)  (P,I)  (J,U)
(B,L)  (I,K)  (H,D)  (B,A)  (I,N)  (H,X)  (P,T)  (J,F)  (T,P)  (F,J)
(L,N)  (K,X)  (D,A)  (L,B)  (K,I)  (D,H)  (T,U)  (F,K)  (U,T)  (K,F);

Commodities: 50
Type 0 arcs: 57
Type 1 arcs: 57
Type 2 arcs: 114
Type 3 arcs: 132
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap; objective 35775050
4424401 MIP simplex iterations
11508 branch-and-bound nodes
absmipgap = 3368.31, relmipgap = 9.41526e-05
adm [*] :=
ABLNIKXHD_A_1 1   ABLNIKXHD_H_4 0   ABLNIKXHD_N_3 1   IPTUJFK_K_1 1
ABLNIKXHD_A_2 1   ABLNIKXHD_I_1 0   ABLNIKXHD_N_4 0   IPTUJFK_K_2 0
ABLNIKXHD_A_3 1   ABLNIKXHD_I_2 1   ABLNIKXHD_X_1 1   IPTUJFK_K_3 0
ABLNIKXHD_A_4 1   ABLNIKXHD_I_3 1   ABLNIKXHD_X_2 1   IPTUJFK_P_1 1
ABLNIKXHD_B_1 1   ABLNIKXHD_I_4 0   ABLNIKXHD_X_3 1   IPTUJFK_P_2 0
ABLNIKXHD_B_2 1   ABLNIKXHD_K_1 0   ABLNIKXHD_X_4 1   IPTUJFK_P_3 1
ABLNIKXHD_B_3 0   ABLNIKXHD_K_2 0   IPTUJFK_F_1 1     IPTUJFK_T_1 0
ABLNIKXHD_B_4 0   ABLNIKXHD_K_3 0   IPTUJFK_F_2 0     IPTUJFK_T_2 0
ABLNIKXHD_D_1 1   ABLNIKXHD_K_4 1   IPTUJFK_F_3 1     IPTUJFK_T_3 1
ABLNIKXHD_D_2 0   ABLNIKXHD_L_1 0   IPTUJFK_I_1 0     IPTUJFK_U_1 0
ABLNIKXHD_D_3 0   ABLNIKXHD_L_2 0   IPTUJFK_I_2 1     IPTUJFK_U_2 0
ABLNIKXHD_D_4 0   ABLNIKXHD_L_3 1   IPTUJFK_I_3 1     IPTUJFK_U_3 1
ABLNIKXHD_H_1 1   ABLNIKXHD_L_4 0   IPTUJFK_J_1 1
ABLNIKXHD_H_2 0   ABLNIKXHD_N_1 0   IPTUJFK_J_2 1
ABLNIKXHD_H_3 0   ABLNIKXHD_N_2 0   IPTUJFK_J_3 1
;
```

The cost of this is **35775050**.

Total Cost of the network is Part 1 + Part 2 = 26292820 + 35775050 = **62067870**

Upper Bound Solution

To calculate the upper bound we still split the networks in to the same two parts. But instead of substituting hubs Q and M with X, we came up with a creative idea. Any data entering into ring QMEGRCOS enters through hub Q and any data leaving the ring QMEGRCOS exits through hub M. So, if there is a flow of data from A to G, the flow is split into A to Q and Q to G. Similarly, if there is a flow from hub G to hub I then the flow is split into G to M and M to I. This method gives us the upper bound.

PART 1 Ring QMEGRCOS

```
Cycles: 1
set NODES[QMEGRCOS] := Q M E G R C O S;

rings [*] :=
QMEGRCOS  6
;

Hubs: 8
set HUB_NODES := Q M E G R C O S;

set RING_NODES :=
QMEGRCOS_Q_1   QMEGRCOS_M_5   QMEGRCOS_G_3   QMEGRCOS_C_1   QMEGRCOS_O_5
QMEGRCOS_Q_2   QMEGRCOS_M_6   QMEGRCOS_G_4   QMEGRCOS_C_2   QMEGRCOS_O_6
QMEGRCOS_Q_3   QMEGRCOS_E_1   QMEGRCOS_G_5   QMEGRCOS_C_3   QMEGRCOS_S_1
QMEGRCOS_Q_4   QMEGRCOS_E_2   QMEGRCOS_G_6   QMEGRCOS_C_4   QMEGRCOS_S_2
QMEGRCOS_Q_5   QMEGRCOS_E_3   QMEGRCOS_R_1   QMEGRCOS_C_5   QMEGRCOS_S_3
QMEGRCOS_Q_6   QMEGRCOS_E_4   QMEGRCOS_R_2   QMEGRCOS_C_6   QMEGRCOS_S_4
QMEGRCOS_M_1   QMEGRCOS_E_5   QMEGRCOS_R_3   QMEGRCOS_O_1   QMEGRCOS_S_5
QMEGRCOS_M_2   QMEGRCOS_E_6   QMEGRCOS_R_4   QMEGRCOS_O_2   QMEGRCOS_S_6
QMEGRCOS_M_3   QMEGRCOS_G_1   QMEGRCOS_R_5   QMEGRCOS_O_3
QMEGRCOS_M_4   QMEGRCOS_G_2   QMEGRCOS_R_6   QMEGRCOS_O_4;

bbdx [*] :=
C  0
E  0
G  1
M  1
O  1
Q  1
R  0
S  0
;

set EDGES :=
```

```
(Q,M)   (E,G)   (R,C)   (O,S)   (Q,S)   (E,M)   (R,G)   (O,C)
(M,E)   (G,R)   (C,O)   (S,Q)   (M,Q)   (G,E)   (C,R)   (S,O);

Commodities: 24
Type 0 arcs: 48
Type 1 arcs: 48
Type 2 arcs: 96
Type 3 arcs: 120
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap;
objective 27338160
11028686 MIP simplex iterations
59760 branch-and-bound nodes
absmipgap = 2652.82, relmipgap = 9.70373e-05
adm [*] :=
QMEGRCOS_C_1 0   QMEGRCOS_G_1 1   QMEGRCOS_O_1 1   QMEGRCOS_R_1 1
QMEGRCOS_C_2 0   QMEGRCOS_G_2 0   QMEGRCOS_O_2 1   QMEGRCOS_R_2 0
QMEGRCOS_C_3 0   QMEGRCOS_G_3 1   QMEGRCOS_O_3 0   QMEGRCOS_R_3 1
QMEGRCOS_C_4 0   QMEGRCOS_G_4 1   QMEGRCOS_O_4 1   QMEGRCOS_R_4 0
QMEGRCOS_C_5 1   QMEGRCOS_G_5 1   QMEGRCOS_O_5 1   QMEGRCOS_R_5 1
QMEGRCOS_C_6 0   QMEGRCOS_G_6 1   QMEGRCOS_O_6 1   QMEGRCOS_R_6 0
QMEGRCOS_E_1 0   QMEGRCOS_M_1 0   QMEGRCOS_Q_1 1   QMEGRCOS_S_1 1
QMEGRCOS_E_2 0   QMEGRCOS_M_2 0   QMEGRCOS_Q_2 1   QMEGRCOS_S_2 0
QMEGRCOS_E_3 0   QMEGRCOS_M_3 0   QMEGRCOS_Q_3 0   QMEGRCOS_S_3 0
QMEGRCOS_E_4 0   QMEGRCOS_M_4 1   QMEGRCOS_Q_4 0   QMEGRCOS_S_4 1
QMEGRCOS_E_5 1   QMEGRCOS_M_5 1   QMEGRCOS_Q_5 0   QMEGRCOS_S_5 0
QMEGRCOS_E_6 0   QMEGRCOS_M_6 0   QMEGRCOS_Q_6 0   QMEGRCOS_S_6 1
;
```

The cost of Part 1 is **27338160**

Part 2 Rings ABLNIKXHD and KIPTUJF.

```
Cycles: 2
set NODES[ABLNIKMQHD] := A B L N I K M Q H D;
set NODES[IPTUJFK] := I P T U J F K;

rings [*] :=
ABLNIKMQHD  4
   IPTUJFK  3
;

Hubs: 15
set HUB_NODES := A B L N I K M Q H D P T U J F;

set RING_NODES :=
ABLNIKMQHD_A_1   ABLNIKMQHD_I_1   ABLNIKMQHD_H_1   IPTUJFK_T_3
ABLNIKMQHD_A_2   ABLNIKMQHD_I_2   ABLNIKMQHD_H_2   IPTUJFK_U_1
ABLNIKMQHD_A_3   ABLNIKMQHD_I_3   ABLNIKMQHD_H_3   IPTUJFK_U_2
ABLNIKMQHD_A_4   ABLNIKMQHD_I_4   ABLNIKMQHD_H_4   IPTUJFK_U_3
ABLNIKMQHD_B_1   ABLNIKMQHD_K_1   ABLNIKMQHD_D_1   IPTUJFK_J_1
```

```
ABLNIKMQHD_B_2   ABLNIKMQHD_K_2   ABLNIKMQHD_D_2   IPTUJFK_J_2
ABLNIKMQHD_B_3   ABLNIKMQHD_K_3   ABLNIKMQHD_D_3   IPTUJFK_J_3
ABLNIKMQHD_B_4   ABLNIKMQHD_K_4   ABLNIKMQHD_D_4   IPTUJFK_F_1
ABLNIKMQHD_L_1   ABLNIKMQHD_M_1   IPTUJFK_I_1      IPTUJFK_F_2
ABLNIKMQHD_L_2   ABLNIKMQHD_M_2   IPTUJFK_I_2      IPTUJFK_F_3
ABLNIKMQHD_L_3   ABLNIKMQHD_M_3   IPTUJFK_I_3      IPTUJFK_K_1
ABLNIKMQHD_L_4   ABLNIKMQHD_M_4   IPTUJFK_P_1      IPTUJFK_K_2
ABLNIKMQHD_N_1   ABLNIKMQHD_Q_1   IPTUJFK_P_2      IPTUJFK_K_3
ABLNIKMQHD_N_2   ABLNIKMQHD_Q_2   IPTUJFK_P_3
ABLNIKMQHD_N_3   ABLNIKMQHD_Q_3   IPTUJFK_T_1
ABLNIKMQHD_N_4   ABLNIKMQHD_Q_4   IPTUJFK_T_2;

bbdx [*] :=
A  1
B  1
D  0
F  0
H  0
I  1
J  1
K  1
L  0
M  1
N  0
P  1
Q  1
T  0
U  0
;

set EDGES :=
(A,B)   (I,K)   (H,D)   (L,B)   (M,K)   (I,P)   (J,F)   (U,T)
(B,L)   (K,M)   (D,A)   (N,L)   (Q,M)   (P,T)   (F,K)   (J,U)
(L,N)   (M,Q)   (A,D)   (I,N)   (H,Q)   (T,U)   (P,I)   (F,J)
(N,I)   (Q,H)   (B,A)   (K,I)   (D,H)   (U,J)   (T,P)   (K,F);

Commodities: 54
Type 0 arcs: 61
Type 1 arcs: 61
Type 2 arcs: 122
Type 3 arcs: 144
CPLEX 12.8.0.0:
<BREAK> (cplex)
CPLEX solution status 13 with fixed integers:
      aborted in phase II
aborted, integer solution exists; objective 36117600
16344737 MIP simplex iterations
42334 branch-and-bound nodes
absmipgap = 1.00793e+06, relmipgap = 0.027907
adm [*] :=
```

```
ABLNIKMQHD_A_1 1
ABLNIKMQHD_A_2 1
ABLNIKMQHD_A_3 1
ABLNIKMQHD_A_4 1
ABLNIKMQHD_B_1 1
ABLNIKMQHD_B_2 0
ABLNIKMQHD_B_3 0
ABLNIKMQHD_B_4 0
ABLNIKMQHD_D_1 0
ABLNIKMQHD_D_2 0
ABLNIKMQHD_D_3 0
ABLNIKMQHD_D_4 1
ABLNIKMQHD_H_1 0
ABLNIKMQHD_H_2 0
ABLNIKMQHD_H_3 0
ABLNIKMQHD_H_4 1
ABLNIKMQHD_I_1 1
ABLNIKMQHD_I_2 0
ABLNIKMQHD_I_3 1
ABLNIKMQHD_I_4 1
ABLNIKMQHD_K_1 0
ABLNIKMQHD_K_2 1
ABLNIKMQHD_K_3 0
ABLNIKMQHD_K_4 0
ABLNIKMQHD_L_1 0
ABLNIKMQHD_L_2 0
ABLNIKMQHD_L_3 0
ABLNIKMQHD_L_4 1
ABLNIKMQHD_M_1 1
ABLNIKMQHD_M_2 0
ABLNIKMQHD_M_3 0
ABLNIKMQHD_M_4 1
ABLNIKMQHD_N_1 0
ABLNIKMQHD_N_2 0
ABLNIKMQHD_N_3 0
ABLNIKMQHD_N_4 1
ABLNIKMQHD_Q_1 0
ABLNIKMQHD_Q_2 1
ABLNIKMQHD_Q_3 1
ABLNIKMQHD_Q_4 0
IPTUJFK_F_1 1
IPTUJFK_F_2 0
IPTUJFK_F_3 1
IPTUJFK_I_1 1
IPTUJFK_I_2 1
IPTUJFK_I_3 0
IPTUJFK_J_1 1
IPTUJFK_J_2 1
IPTUJFK_J_3 1
IPTUJFK_K_1 0
IPTUJFK_K_2 0
IPTUJFK_K_3 1
IPTUJFK_P_1 1
IPTUJFK_P_2 0
IPTUJFK_P_3 1
IPTUJFK_T_1 1
IPTUJFK_T_2 0
IPTUJFK_T_3 0
IPTUJFK_U_1 0
IPTUJFK_U_2 0
IPTUJFK_U_3 1
;
```

The cost of Part 2 is **36117600**

Total Upper Bound Cost is 27338160 + 36117600 = **63455760**

Optimality Gap for the Barry network

The optimality gap is calculated by $\frac{63455760-62067870}{62067870}$

which is equal to **0.0224 or 2.24%**

Creative Ideas we tried to incorporate

To calculate the upper bound of the barry network, we decided to use hubs Q and M as entry and exit gates. Just like a parking garage where there is one path for entry and another path to exit, we consider the flow of data as cars where data enters the ring at hub Q and exits the ring at hub M. For instance, the flow from hub A to G is split into A to Q and Q to G and the flow from hub G to L is split into G to M and M to L.