AN INTEGRATED MODEL OF RURAL ROAD NETWORK DESIGN AND MULTI PUBLIC FACILITY LOCATIONS IN DEVELOPING COUNTRIES*

by Salpiseth HENG**, Yasuhiro HIROBATA***, and Hitomi NAKANISHI****

1. Introduction

In developing countries, rural transport networks connecting the rural population to their farms, local markets, and social services such as schools and health centers, are mostly in poor condition. Poor geographical accessibility has made rural citizens isolated from opportunities to improve quality of life[1)]. Under this background, claims that by eliminating isolation, better roads and facility locations reduce vulnerability and income variability have been made. It is vital to determine appropriate network design and facility locations simultaneously as there is significant interaction[2), 3)] between them. It would assist decision makers on how to make a choice effectively under limited fund constraints to build schools, expand hospitals, or improve road links[2)].

Transportation network design and facility location theory have been extensively studied in the past, almost entirely independently each other. This is unfavorable because the very definition of optimal locations of facilities, both private and public in order to serve residents, is constrained by the structure of the designed transportation network. When the network is designed improperly, residents get extremely poor service even when facilities are located optimally.

Therefore, in addressing the problem above, it is necessary to investigate models where rural transportation networks are designed considering present and future facility locations. In this model, transportation network configuration and new multi public facility locations are to be economically designed simultaneously to allow the residents of the network to avail of the services supplied by these new facilities and some existing ones whose location are already known.

This paper gives a contribution over previous similar research papers[3), 4)]. With a different solution approach, this research considers multi-type facilities, road surface options for improvement, existing facility location and desirable travel distance for rural dwellers. Modeling with continuous facility variables and by a simulation on real network, this study provides an optimal rural road network configuration connecting all villages to the network.

2. Model Definition and Assumptions

Figure 1 illustrates a typical rural transport network comprising village nodes connected to each other by road link. Road links with dotted and continuous lines are existing tracks or roads in poor condition; and are considered as candidate links for improvement with options of road surface (earth, gravel or asphalt). Each village nodes are taken into account as candidate sites for adding more new multi facilities (markets, schools and health centers) to the existing ones.

The integrated model aims to minimize the total travel cost of the rural population. The model deals with access to the nearest main roads, and access to the nearest public facilities. As available national budget for infrastructure investment in the developing countries is critical, a budget sensitivity analysis will be carried out throughout this study.

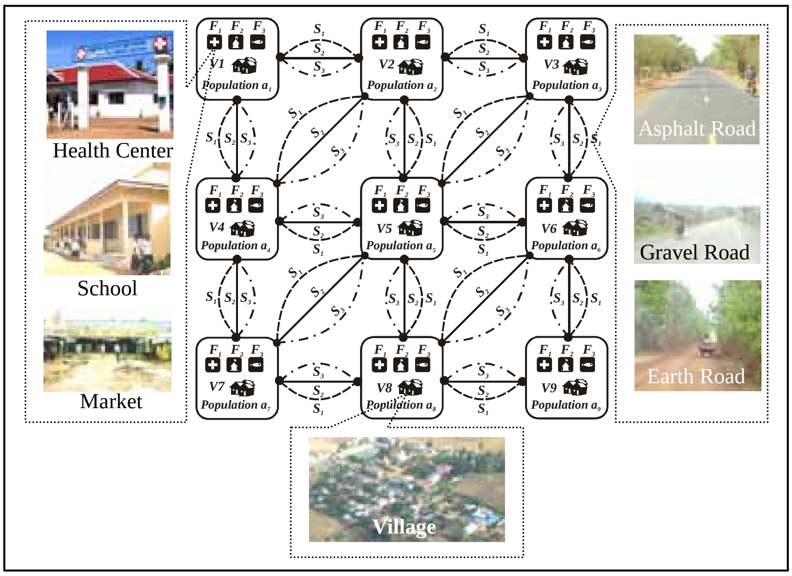

Figure 1: Components of integrated model of rural road network design and rural public facility allocation

*Keywords: integrated model, rural road network, multi public facility locations, developing countries
**Graduate Student, Dept. of Architecture and Civil Engineering, Toyohashi University of Technology,
(1-1, Hibarigaoka, Tempaku-cho, Toyohashi city, 441-8580 Japan, TEL 0532-44-5625, FAX 0532-44-6831)
***Member of JSCE, Dr. Eng., Dept. of Architecture and Civil Engineering, Toyohashi University of Technology,
(1-1, Hibarigaoka, Tempaku-cho, Toyohashi city, 441-8580 Japan, TEL 0532-44-6833, FAX 0532-44-6831)
****Member of JSCE, PhD (Engineering), Dept. of Architecture and Civil Engineering, Toyohashi University of Technology,
(1-1, Hibarigaoka, Tempaku-cho, Toyohashi city, 441-8580 Japan, TEL 0532-44-6842, FAX 0532-44-6831)

Necessary assumptions made throughout this study are stated as follows: 1) Congestion and the effect of traffic volume have not been considered as traffic flows are low in the rural areas of developing countries, even though this is one of the main concerns in developed countries. 2) All villages are connected to the network regardless of their sizes. 3) Each village node represents a demand point. 4) Each village demand is restrictively assigned to a single corresponding facility. 5) Facilities may only be located at the nodes. 6) The network is a resident-to-server system in which the demands themselves are travel to the facilities to be served. 7) The facility interaction is not considered in this paper. 8) Facility location cost is linearly proportional to its size.

3. Model Formulation

The notations used throughout the paper are: N and L are sets of village nodes and road links respectively. S is a set of road surface options. F is a set of facility types. $O, D \subseteq N$ are sets of demand and supply (origin and destination) nodes respectively. K_{od} is a set of paths connecting OD pair od. C_{ij}^{s} is travel cost per unit flow on link (i, j) where $C_{ij}^{s} = d_{ij}.c_{ij}^{s}$. c_{ij}^{s} is travel cost per unit flow and distance of traveling over surface type s ($s = 1, 2, 3$ for asphalt, gravel and earth respectively) on link (i, j). d_{ij} is link distance (i, j) from the i^{th} node to j^{th} node. q_{od} is trip rate between OD pair od where $q_{od} = \sum_{F=1}^{3} y_{od}^{F}.a_{o}^{F}$. a_{o}^{F} is demand size at demand node o for facility F ($F = 1, 2, 3$ for health center, school and market respectively). EY_{d}^{F} is existing facility capacity at supply node d. D_{max}^{F} is maximum total travel distance for each citizen to get services from facility type F. B represents total investment budget. α_{d}^{F} is the coefficient of allocation cost of facility type F at supply node d. In real-life planning, the coefficient of facility cost α_{d}^{F} should be made on the basis of factors such as location costs of the facility (land price), available labor and material resources at this site or other externalities such as the case where governments target specific under-developed regions for development. CC_{ij}^{s} is cost of network improvement link (i, j) with surface type s. $\delta_{ij,r}^{od}$ equals 1 if link (i, j) is on path r between OD pair od, 0 otherwise.

Then, the decision variables are:

$$X_{ij}^{s} = \begin{cases} 1 & \text{if a link } (i, j) \text{ is built with surface type } s; \\ 0 & \text{otherwise} \end{cases} \qquad y_{od}^{F} = \begin{cases} 1 & \text{if demand at node } o \text{ is assigned to a facility } F \text{ located at supply node } d. \\ 0 & \text{otherwise} \end{cases}$$

x_{ij}^{s} - Flow on link (i, j) with surface s; f_{r}^{od} - Flow on path r connecting OD pair od;

Y'^{F}_{d} - Facility capacity built at supply node d (demand can be served by a facility at supply node d);

The network design problem which seeks to minimize total transportation costs subject to budget and spatial constraints can be formulated as follows:

$$\text{Minimize } \sum_{s=1}^{3} \sum_{(i,j)\in L} C_{ij}^{s}.x_{ij}^{s} \tag{1}$$

Subject to

$$\sum_{r\in K_{od}} f_{r}^{od} = q_{od} = \sum_{F=1}^{3} y_{od}^{F}.a_{o}^{F} \qquad \forall (o,d) \in O, D \tag{2}$$

$$\sum_{s=1}^{3} x_{ij}^{s} = \sum_{(o,d)\in O,D} \sum_{r\in K_{od}} f_{r}^{od} \delta_{ij,r}^{od} \qquad \forall (i,j) \in L \tag{3}$$

$$\sum_{F=1}^{3} \sum_{d\in D} \alpha_{d}^{F}.Y'^{F}_{d} + \sum_{s=1}^{3} \sum_{(i,j)\in L, i>j} CC_{ij}^{s}.X_{ij}^{s} \le B \tag{4}$$

$$\sum_{o\in O} a_{o}^{F}.y_{od}^{F} - \left(Y'^{F}_{d} + EY_{d}^{F}\right) \le 0 \qquad \forall d \in D,\ \forall F \in \mathsf{F} \tag{5}$$

$$a_{o}^{F}.y_{od}^{F} - \left(Y'^{F}_{d} + EY_{d}^{F}\right) \le 0 \qquad \forall o, d \in O, D,\ \forall F \in \mathsf{F} \tag{6}$$

$$x_{ij}^{s} \le X_{ij}^{s}.\sum_{F=1}^{3} \sum_{o\in O} a_{o}^{F} \qquad \forall (i,j) \in L, \forall s \in S \tag{7}$$

$$X_{ij}^{s} = X_{ji}^{s} \qquad \forall (i,j), (j,i) \in L,\ \forall s \in S \tag{8}$$

$$\sum_{s=1}^{3} X_{ij}^{s} = 1 \qquad \forall (i,j) \in L \tag{9}$$

$$\sum_{d\in D} y_{od}^{F} = 1 \qquad \forall o \in O,\ \forall F \in \mathsf{F} \tag{10}$$

$$y_{od}^{F} \le y_{dd}^{F} \qquad \forall o, d \in O, D,\ \forall F \in \mathsf{F} \tag{11}$$

$$\sum_{(i,j)\in L} \delta_{ij,r}^{od}.d_{ij}.y_{od}^{F} \le D_{max}^{F} \quad \forall o, d \in O, D,\ \forall r \in K_{od},\ \forall F \in \mathsf{F} \tag{12}$$

$$y_{od}^{F} \in \{0,1\};\ X_{ij}^{s}, X_{ji}^{s} \in \{0,1\};\ Y'^{F}_{d} \ge 0;\ x_{ij}^{s} \ge 0;\ f_{r}^{od} \ge 0,\ \forall (i,j) \in L, \forall i, j \in N, \forall o, d \in O, D,\ \forall s \in S, \forall F \in \mathsf{F}, \forall r \in K_{od} \tag{13}$$

The objective function minimizes total transportation cost of the population. Eq. (2) and (3) describe flow conservation. Eq. (4) indicates that the total expenditures (facilities and links construction cost) is constrained to an investment budget. The term of link construction expenditure is to be divided by 2 as we need to build only one link either (i, j) or (j, i) on which both flows $i \rightarrow j$ and $j \rightarrow i$ can appear. Eq. (5) restricts total demand assigned to a facility not exceed the capacity of the facility. Eq. (6) states that demands only assigned to open facilities. Eq. (7) ensures that flow on link can occur only if the link is constructed. Constraints (8) and (9) define that one link in both directions $i \rightarrow j$ and $j \rightarrow i$ is to be paved with only one type of surface. These constraints also guarantee all links are to be connected and at least are built with the cheapest surface option (earth road) however there may be no flow on some links. This would provide more accessibility to many villagers; transport operators could service the district more efficiently and a third benefit may be providing alternative access if any link of the shortest path is closed either for repair or as a result of natural disasters. Eq. (10) requires each demand node assigned to exactly one facility. Eq. (11) eliminates the possibility of cross haulage by restricting assignments to communities which assign to themselves: $y^F_{od} + \sum_{k=1,k\neq d}^{n} y^F_{dk} \leq 1$. If village o is assigned to a central facility in village d ($y^F_{od} = 1$), then village d cannot reassign the people to village k ($y^F_{dk} \leq 0$ for the people to village k) $\Rightarrow y^F_{od} \leq y^F_{dd}$. Eq. (12) restricts maximum total travel distance for each citizens to get services from facility. In planning to improve access through location of a facility, a catchment area needs to be defined. A desirable upper limit for travel distance (travel time) from any village to facility center should not be exceeded[1)]. For instance because of targeting at optimizing the total cost in this model, it may bias the location of facility to the populated areas which would penalize other isolated ones with low density. Therefore, since individual travel distance (travel time) influences their welfare and in order to avoid high inequality in accessibility to public services, it is essential to consider the upper limit of travel distance of each citizen in the integrated model corresponding to each type of facilities. So D^F_{max} is a factor to impose restriction on the decision variable of customer assignment y^F_{od}. It means the total travel distance is a barrier influencing the decision making of citizen whether to travel to acquire services from a facility type F at a certain location. This results in a constraint to facility decision variables Y'^F_d where the facility should be located. Finally, (13) are integrality and non-negative constraints.

4. Solution Method

As the integrated model above is a combined facility location/ network design problem in which facilities are capacitated, we call it the Capacitated Facility Location/ Network Design Problem (CFLNDP). To solve this problem effectively to optimality, the complex mathematical model was solved using MPL for Windows as the modeling language with CPLEX 10.0's MIP solver.

5. Examples and Computational Results:

In this paper, we begin by proposing a model that incorporates facility location in the decision-making process involved in the design of a rural transportation network as mentioned above. Local government is assumed to be responsible for constructing a transportation network with adding several new different types of public facilities to provide efficient services to a group of residents who will patronize the closest facility. The result of this study would demonstrate that integrated models of facility location and network design can be solved to optimality despite of its complex mathematical formulation.

a) Simple Network:

Since this is essentially a first step in the confluence of these two areas, we begin by testing the integrated model with a simple network with 4 candidate nodes and 5 candidate links as shown in Figure 2. This work seeks to design a cost-effective transportation network and facility location that will be used by the villagers to access to the public services provided by three types of facility, by taking into account given fixed locations of existing facilities. The test network is generated with approximate real cost parameter in a developing country.

In order to understand the model's behavior considering different budget scenarios, a sensitivity analysis is made in this study. It is interesting to find out how the topology of the network is determined optimally. With an available budget, the results from the analysis would help to identify how much we should invest in facility and link; which link and what level of improvement we should deal with; and which facility type and where we should built to reach optimality.

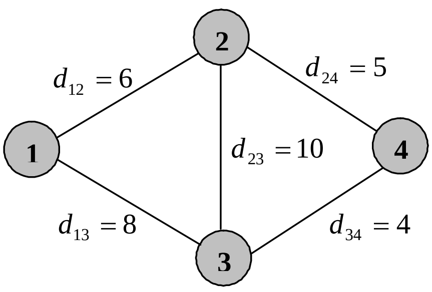

Figure 2: Simple network

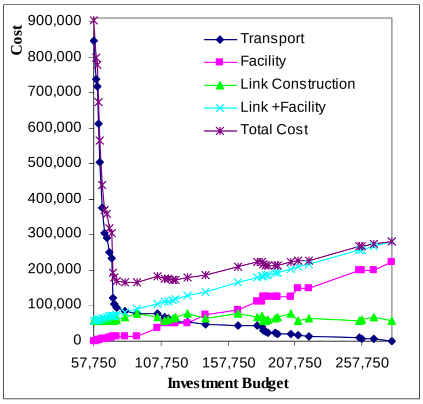

Figure 3: Expenditure vs. investment budget (more existing facility case)

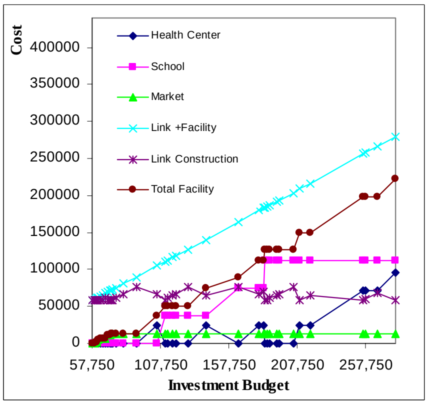

Figure 4: Each facility and link cost vs. investment budget (more existing facility case)

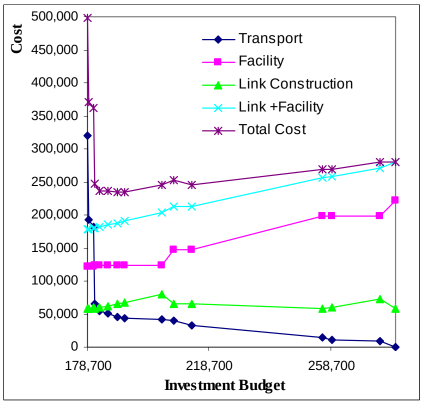

Figure 5: Expenditure vs. investment budget (less existing facility case)

Overview of simulation results:

- 1st case: when more existing facilities are available, as budget increases, the tradeoff between expenditure and investment budget in Figure 3 shows that the total investment cost (link and facility expenditure) increases linearly from connecting the link with the cheapest surface option $B = \sum_{(i,j)\in L} CC_{ij}^{s_3}$ to $B = \sum_{F=1}^{3}\sum_{j\in N} \alpha_j^F . Y'^F_j + \sum_{s=1}^{3}\sum_{(i,j)\in L} CC_{ij}^{s} . X_{ij}^{s}$.
  The graph in Figure 4 clearly demonstrates that the total facility cost increases whereas cost of some facility such as health facility and the link construction expenditure fluctuates to search for an optimal solution.
- 2nd case: when few existing facilities are available, Figure 5 illustrates that as budget rises, much resource is required to be initially allocated to build more facility to sufficiently supply the total demand and to connect all links with the cheapest surface option. The expenditure increases from $B = \sum_{F=1}^{3}\sum_{j\in N} \alpha_j^F . Y'^F_j + \sum_{(i,j)\in L} CC_{ij}^{s_3}$ to

$$\sum_{F=1}^{3}\sum_{j\in N} \alpha_j^F . Y'^F_j + \sum_{s=1}^{3}\sum_{(i,j)\in L} CC_{ij}^{s} . X_{ij}^{s} .$$

For both cases, the optimal solution at each budget level is reached to minimize the total travel cost by searching for an optimal combination value of the decision variables (link improvement and facility location).

b) Real Network:

After successfully testing the simple network, the simulation work is to be challenged on real rural road network with real input parameters. Puok district with approximate area of 1,090 km^2 and a 1998 population of 110,392 in Siem Reap Province of Cambodia, located about 15 km from the World Heritage Angkor Wat temple, is taken as the study area in this research. The result from the model solution and analysis will be presented at the conference.

6. Conclusion

In this research, we have studied the problem of designing a rural transportation network to provide better accessibility to several given public service facilities for the rural residents around the network. The problem can be tackled by solving this model searching for potential location and size of each facility type along with cost-effective road improvement. The integrated model is used to solve a problem where both the facility location and the road network design are decision variables. Throughout the budget sensitivity analysis to observe the model's behavior, an effective process for the efficient allocation of resources to transport infrastructure and public facility improvement is identified. Therefore the proposed model copes with the improvement of road network, along with provision of other public facilities, is expected to be a useful tool to invest the restricted public resources efficiently to achieve economic goals in the developing nations such as Cambodia.

References

1) Rahman, S. and Smith, D.K.: Use of location-allocation models in health service development planning in developing nations, European Journal of Operational Research, Vol.123, pp.437-452, 2000.
2) Daskin, M.S. and Owen, S.H.: Location models in transportation, in Handbook of Transportation Science, Hall, R.W. (eds.), Kluwer Academic Publishers, Norwell, MA, ch.10, pp. 311-360, 1999.
3) Melkote, S. and Daskin, M.S.: An integrated model of facility location and transportation network design, Transportation Research Part A, Vol. 35, pp.515-538, 2001.
4) Melkote, S. and Daskin, M.S.: Capacitated facility location-network design problems, European Journal of Operational Research, Vol.129, pp.481-495, 2001.