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AN INTEGRATED MODEL FOR OPTIMIZING RURAL ROAD NETWORK AND PUBLIC FACILITY LOCATION IN DEVELOPING COUNTRIES*

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1. Introduction

In developing countries, rural road 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 residents isolated from opportunities which improve quality of life[1)]. Under this background, claims have also been made that by reducing isolation, better roads and facility locations reduce vulnerability and dampen income variability. Providing an adequate rural road network and proper planning of public facilities is really important to cater for the needs of rural residents. While several evidences are showing there is significant interaction of the network with facility locations, it is meaningful to determine the network design and facility locations simultaneously[2), 3)]. A study on planning of rural roads and public facility locations in a comprehensive integrated manner would help to address the essential questions of the resource allocation. 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)].

Moreover, 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 study, transportation network configuration and new multi public facility locations are to be optimally designed simultaneously to allow the residents of the study area to avail of the services supplied by these new facilities and some existing ones whose location are already known. This research gives a contribution over previous similar research papers[3), 4)]. With a different solution approach, this research considers multi-type public facilities (health centers, primary schools, and rural markets) and several road surface options (bituminous, gravel, and earth) for cost-effective improvement. Desirable travel distances for rural dwellers are also taken into account throughout this study. This model provides an optimal rural road network configuration connecting all villages to the network.

2. Reviews on Related Papers

The reviews of previous studies relating to rural road network planning, public facility locations models, and integrated models of transportation network design and facility locations are made thoroughly in the recent works written by Heng *et al.* [5)]. Heng *et al.* [5)] focuses on the research's originality, paper reviews on related research works, characteristic of the rural road network problem in developing countries, and discussion on constraint parameters. On the other hand, the present paper concentrates mainly on solution method and computational results of the integrated model.

As illustrated in Heng *et al.* [5)], two related papers of research done by Melkote and Daskin[3), 4)] formulate a model of the network design with facility locations. By generalizing the classical simple plant location problem, the integrated model of facility location and transportation network design was applied to analyze the transportation planning scenarios. Suffering from a weak LP relaxation, "Supernode" and "Superlink" are introduced to the network in order to formulate the Uncapacitate Facility Location/Network Design Problem as a special case of pure network design problem[3)]. Similarly, the Capacitate Facility Location/ Network

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Design Problem is formulated through introduction on the extension of the classical Capacitate Facility Location where the network configuration is determined endogenously[4]. Sensitivity analysis for different cases has been conducted throughout the two papers to observe the performance of the formulated model.

However, those studies provided a limited application by simulating only on testing network. There has been no simulation of those integrated models on real network especially applying on rural transportation network and most of the location models do not consider multi-public facilities.

3. Model Formulation

(1) Definition and assumptions

Rural road network forms the basic network within a rural area and serve main local traffic. It links up district centers to villages. It needs to be improved with sufficient capacity and good quality in order to enhance the rural accessibility. The factors affecting rural access are interactive and cannot be considered in isolation. An integrated system approach is therefore needed for effective accessibility planning in which all the relevant factors and their interactions are properly taken into account. For planning rural road network, a hierarchal system needs to be developed as it is necessary to define the internal systems which are the subject of the accessibility planning and the external system that influences them (Figure 1). The internal system should cover an appropriate geographical area encompassing interlinked villages and match the aims of the planning study. The external system should cover all routes, major rural centers, and facilities to which the internal system needs to access and people could benefit from. It is clear that the network design problem for rural road network in developing nations is somewhat different from that for developed countries. The networks in developing countries are being planned around existing roads and very few of the rural road links may already exist. Each village nodes are taken into account as candidate sites for adding more new public facilities. The model suggested in this study aims to achieve least total cost. The least total cost is a concept developed for utility planning that is being applied to transport. The goal of least total cost is to minimize the total societal cost of meeting services needs. The total cost comprises all costs associated with construction and operation of a road network over its entire life including all money spent by producers (government) and consumers (rural residents). The least total cost calculation refers to the trade-offs that government and residents make between use of their financial resources. 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. 2) All villages are connected to the network regardless of their sizes. 3) Facilities may only be located at the village nodes. 4) The network is a resident-to-server system in which the residents themselves are travel to the facilities to be served. 5) Residents would choose the closest facilities. 6) The facility interaction and the attractiveness among facilities are not considered. 7) All candidate links are to be connected, at least constructed with the cheapest level (earth road). 8) Same unit travel costs for each road surface are applied to each rural resident’s travel costs.

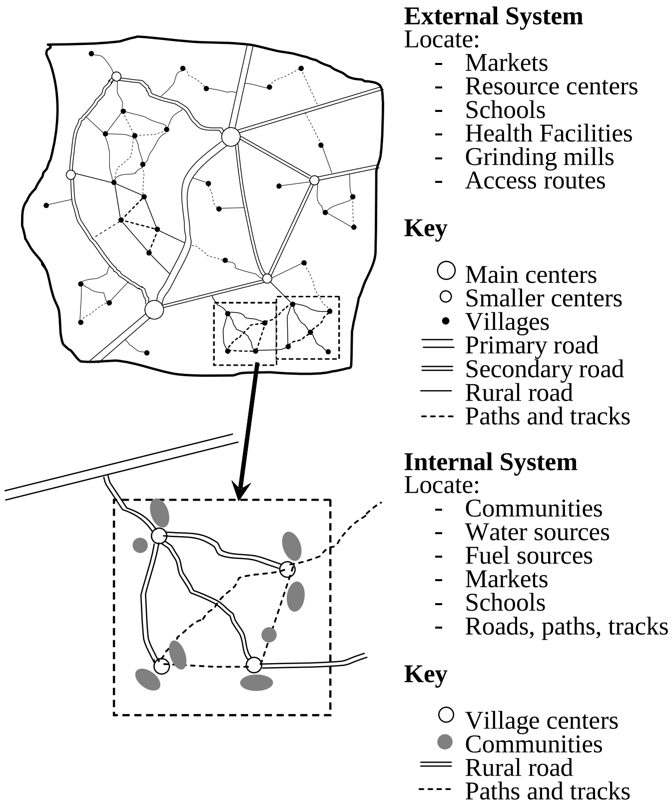


Figure 1: Integrated system for rural road planning

(2) Mathematical formulation

By assuming the residents to be on a number of village nodes of a given road network, the network is considered as a directed graph $G=(N,L)$ where N and L are sets of village nodes and road links respectively. The notations used throughout the mathematical formulation are: S is set of road surface options ($S=(s_1,s_2,s_3)$ for asphalt, gravel and earth respectively). F is the set of facility types ($F=(F_1,F_2,F_3)$ for health centers, primary schools and rural markets respectively). O,D are sets of demand and supply nodes respectively ($O,D\subseteq N$). K_{od} is set of paths connecting OD pair od . d_{ij} is link distance from the node i to node j . C_r^{od} is travel cost per unit flow on path r 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 on link (i,j) . a_o^F is demand size at demand nodes o for facility F . q_{od}^F is trip rate between OD pair od where $q_{od}^F = y_{od}^F.a_o^F$. D_{max}^F is maximum total travel distance for each resident to get services from facility type F . B is an available investment budget. EY_d^F is existing facility capacity at supply nodes d . FC_d^F is capacity of one new facility F or minimum size of one new facility F to be allocated at any supply node d . α_d^F is coefficient of allocation cost of facility type F at each supply node d . CC_{ij}^s is cost of improving 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. β^F is maximum percentage of total number of new facilities F to total number of existing facilities F . The decision variables in this model are: $X_{ij}^s=1$ if a link (i,j) is built with surface type s , 0 otherwise; Y_d^F is numbers of new facilities F built at supply nodes d , where $Y_d^F \in N$. Link flow variable x_{ij}^s on link (i,j) with surface s defined by X_{ij}^s and Y_d^F is introduced to the model to calculate the total transportation cost. Additionally, in order to solve the mathematical formulation of the integrated model, other two variables are also used: y_{od}^F is fraction of demand for facility F at node o assigned to a facility F at node d where $0\le y_{od}^F \le 1$; $f_r^{F,od}$ is flow of demand for facility F on path r connecting OD pair od . It is vital to recognize that there is no unique optimum network. Having defined a specific objective and a set of constraints, then a model may generate a strictly mathematical optimum. The goal of this study is to investigate the fundamental question of public resource allocation to attain minimum total cost. The objective function of the integrated model aims to optimize the total cost as follows:

$$\text{Minimize} \sum_{s=1}^{3}\sum_{(i,j)\in L} C_{ij}^s \cdot x_{ij}^s + \sum_{F=1}^{3}\sum_{d\in D}\alpha_d^F \cdot FC_d^F \cdot Y_d^F + \sum_{s=1}^{3}\sum_{(i,j)\in L, i<j} CC_{ij}^s \cdot X_{ij}^s \qquad (1)$$

This objective function is subjected to several constraints including budget constraint, capacity constraint of facility, and limitation of maximum total number of new facilities to be allocated. A number of additional valid equalities and inequalities such as constraints of flow conservation; flow occurs only on constructed link; all demand must be served; elimination of possible cross haulage; and integrality and non-negative constraints are added to strengthen the LP relaxation of the integrated model. Restriction on maximum traveling distance for residents to get services from each facility is also considered in the model.

However, as budget constraint is very important in this study, we should consider different scenarios of budget design problem. The summation of link and facility construction costs subjected to a budget is added as a constraint. This would make the complex mathematical formulation becomes easier to be solved as choosing a good formulation for a mixed-integer optimization model can drastically reduce its load for solution.

The Capacitated Facility Location/Network Design Problem (CFLNDP) which seeks to minimize total transportation costs of the population subject to budget and spatial constraints should be reformulated as follows:

$$\text{Minimize} \quad \sum_{s=1}^{3}\sum_{(i,j)\in L} C_{ij}^s \cdot x_{ij}^s \qquad (2)$$

$$\text{Subject to} \quad \sum_{r\in K_{od}} f_r^{F,od} = q_{od}^F = y_{od}^F \cdot a_o^F \qquad \forall (o,d)\in O,D,\ \forall F\in \mathcal{F} \qquad (3)$$

$$\sum_{s=1}^{3} x_{ij}^{s} = \sum_{F=1}^{3} \sum_{(o,d)\in O,D} \sum_{r\in K_{od}} f_r^{F,od} \delta_{ij,r}^{od} \quad \forall (i,j)\in L \tag{4}$$

$$\sum_{F=1}^{3} \sum_{d\in D} \alpha_d^F \cdot FC_d^F \cdot Y_d^F + \sum_{s=1}^{3} \sum_{(i,j)\in L, i<j} CC_{ij}^s \cdot X_{ij}^s \le B \tag{5}$$

$$\sum_{o\in O} a_o^F \cdot y_{od}^F - (FC_d^F \cdot Y_d^F + EY_d^F) \le 0 \quad \forall d\in D, \forall F\in \mathcal{F} \tag{6}$$

$$\sum_{d\in D} FC_d^F \cdot Y_d^F - \beta^F \cdot \sum_{d\in D} EY_d^F \le 0 \qquad \forall F\in \mathcal{F} \tag{7}$$

$$x_{ij}^s \le X_{ij}^s \cdot \sum_{F=1}^{3} \sum_{o\in O} a_o^F \qquad \forall (i,j)\in L, \forall s\in S \tag{8}$$

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

$$\sum_{s=1}^{3} X_{ij}^s = 1 \quad \forall (i,j)\in L \tag{10}$$

$$\sum_{d\in D} y_{od}^F = 1 \quad \forall o\in O, \forall F\in \mathcal{F} \tag{11}$$

$$y_{od}^F \le y_{dd}^F \qquad \forall o,d\in O,D, \forall F\in \mathcal{F} \tag{12}$$

$$0 \le y_{od}^F \le 1 \quad \forall o,d\in O,D, \forall F\in \mathcal{F} \tag{13}$$

$$y_{od}^F \ge 0;\ X_{ij}^s, X_{ji}^s \in \{0,1\};\ Y_d^F \in N = \{0,1,2,\ldots n\};\ x_{ij}^s \ge 0;\ \ f_r^{F,od} \ge 0$$

where $\sum_{(i,j)\in L} \delta_{ij,r}^{od} \cdot d_{ij} \le D_{\max}^F$; $\forall (i,j)\in L$, $\forall i,j\in N$, $\forall o,d\in O,D \subseteq N$, $\forall s\in S$, $\forall F\in \mathcal{F}, \forall r\in K_{od}$ (14)

Equation (3) and (4) describe flow conservation. Eq. (5) 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 spent 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. (6) restricts total demand assigned to a facility not exceed the capacity of the facility. Eq. (7) limits maximum total number of new facilities to be allocated. Eq. (8) ensures that flow on link can occur only if the link is constructed. Constraints (9) and (10) define that one link in both directions $i\rightarrow j$ and $j\rightarrow i$ are to be paved with only one type of surface. These constraints also guarantee all links are to be connected, at least built with the cheapest surface option (earth road). Eq. (11) states that summation of all fractions of demand for facility *F* at any node o assigned to all facility *F* at node d equal unity. Eq. (12) eliminates the possibility of cross haulage by restricting assignments to communities which assign to themselves: $y_{od}^F + \sum_{k=1,k\neq d}^{n} y_{dk}^F \le 1$. If demand at village o is fully assigned to a certain facility in village d ($y_{od}^F = 1$), then village d cannot reassign the people to village k ($y_{dk}^F \le 0$ for the people to village k) $\Rightarrow y_{od}^F \le y_{dd}^F$. Eq. (13) is constraint for demand assignment variables. Finally, (14) expresses integrality and non-negative constraints. Maximum traveling distance for residents to get services from each facility is considered in the model. D_{max}^F is a factor to impose restriction on the path flow variable $f_r^{F,od}$ which affects the decision variable of customer assignment y_{od}^F. It means that the total travel distance is a barrier influencing the decision making of residents whether to travel to acquire services from a facility type *F* at a certain location. This result is a constraint to facility decision variables Y_d^F where the facility should be located.

Several aspects of the integrated model are worth noting. When $\beta^F = 0$ and all the network link is improved with *S3* only: $X_{ij}^{s_3} = 1$, the model is a "Shortest Path" problem. When $\beta^F = 0$, the integrated model appears as "Pure Network Design Problem" (PNDP). When all the network link is improved with S3 only: $X_{ij}^{s_3} = 1$, the model becomes "Pure Capacitated Facility Location Problem" (PCFLP). Therefore the integrated model (CFLNDP) is the general case of other classical models such as Shortest Path Problem, PNDP and PCFLP.

4. Solution Method and Example of Computation

(1) Solution method

It is common practice to relate computation time to problem size. Traditionally, the size of an instance of an optimization problem has been described by its number of variables and number of constraints. Simulated with real network in this study, there are many variables and constraints as a number of public facility types and some road surface options are considered in this integrated model. This would make the problem become difficult to solve. Moreover, the problem of integrated facility location and network design illustrated above is likely to be very difficult to solve since it combines two NP-hard problems: facility location and network design. To solve this problem, the computational complexity of the integrated model was reduced to a shortest path problem and solved by Dijkstra algorithm. As the Dijkstra's algorithm is a polynomial algorithm, the all-pairs shortest path problem uses $O(n)$ times of the Dijkstra's algorithm. Then the all-pairs shortest path problem of the integrated model polynomially reduces to the shortest path tree problem and can be solved in polynomial time. Therefore, shortest route sets for each O-D pair of different networks which are randomly improved with different road surface levels were defined to be generated by the integrated model. The shortest path using "Dijkstra" algorithms is easily coded. Different random networks as shown in Figure 2 are selected to simulate to find sets of shortest routes. All obtained shortest paths are checked to select only unique shortest path to avoid same paths in the set.

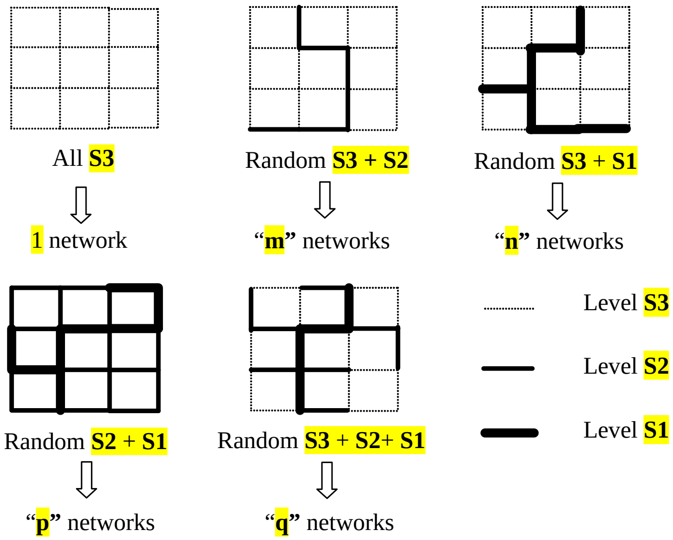


Figure 2: Shortest paths from random networks

The integrated model in this research was generated by using MPL modeling language and solved using the CPLEX 10.0 MIP solver. The model simulation was carried out using the dual simplex algorithm with the default hybrid reduced/devex cost. All problems were simulated with a time limit of 20 min imposed on the branch-and-bound algorithm. All simulations were performed on Windows XP professional Intel Pentium CPU 3.00 GHZ and RAM 1.99 GB.

(2) Simple network

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.

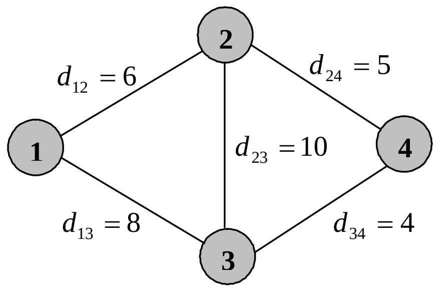


Figure 3: Simple network

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 3. 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.

(3) Overview of simulation results

1st case: when more existing facilities are available, as budget increases, the tradeoff between expenditure and investment budget in Figure 4 shows that the total investment cost (link and facility expenditure) increases linearly from connecting all links only with the cheapest surface option S3 to upgrading link with higher standard (S1 and S2) along with facility allocation. The graph in Figure 5 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 6 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 spends on building all links with the lowest level S3 and allocating more facilities. Some links are upgraded with higher quality as the budget increases.

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).

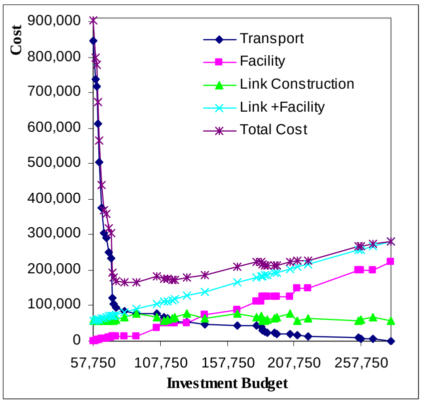


Figure 4: Expenditure vs. investment budget (more existing facility case)

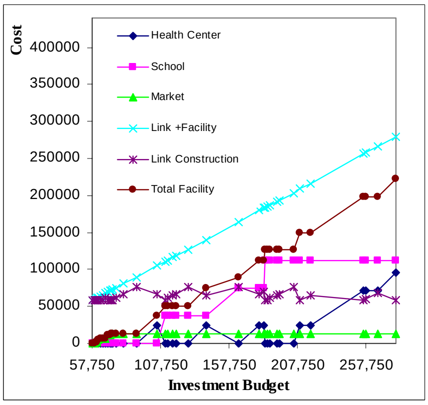


Figure 5: Each facility and link cost vs. investment budget (more existing facility case)

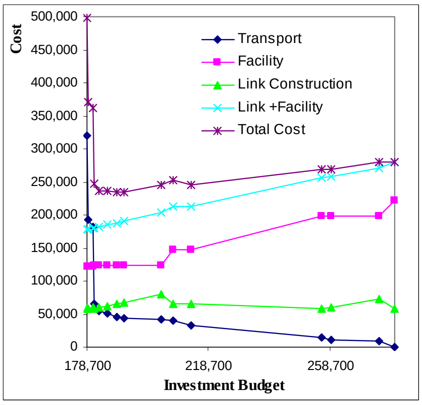


Figure 6: Expenditure vs. investment budget (less existing facility case)

5. Model Application and Validation in Real Networks

In order to prove the applicability and validity in real networks, the integrated model is to be tested on rural road network in Puok district of Cambodia by using real parameters. The characteristics of rural road network in Puok district share a common problem as the ones in developing countries [6]. Puok district has nearly 130,000 inhabitants in 2005 and the center is located about 15 km from Angkor Wat Temple (Figure 7). With approximately area of 1,090 km^2, there are 16 communes and 154 villages. As shown in the Figure 8, there are 61 primary schools, 7 health centers and 1 district and 3 commune markets distributed within the district. There are totally 181 links (about 627 km), among which 14 links (54 km) are good-condition national roads with two-lane asphalt surface. 14 links (50 km) and 153 links (523 km) are provincial roads and rural roads which are considered as candidate links for improvement in this study.

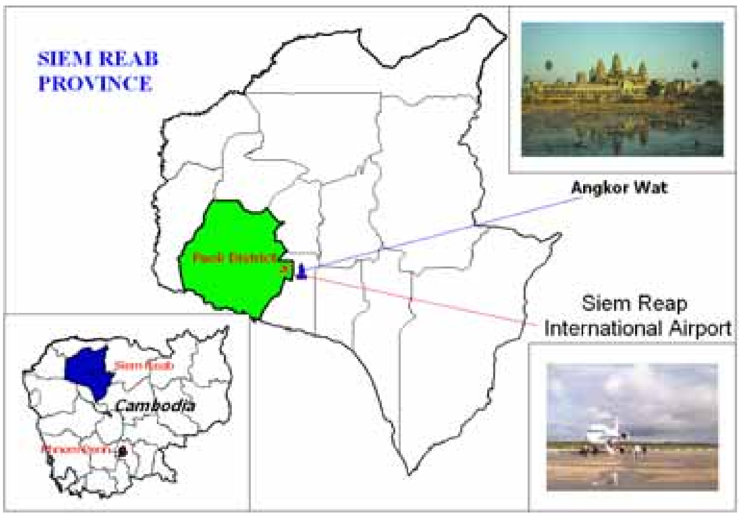


Figure 7: Location of Puok district

The time period for the analysis is 15 years post-construction, i.e. 2005 through 2020. For the fifteen year analysis, the growth was modeled by assuming that the number of Puok residents would increases at the current annual population growth, two percent. In Cambodia, economic growth is stronger in the cities than in the countryside. The values of time of rural inhabitant per hour derived from average household income used in this paper are: \$0.066 for village travelers, \$0.125 for motorcycle drivers and \$0.313 for car drivers.

Although the resident's income has been slightly increased, there is a potential for quick economic growth in Puok district, for instance, through increasing agricultural products to supply many restaurants and hotels in Siem Reap town. Therefore we would study with two scenarios: without economic growth (conservative

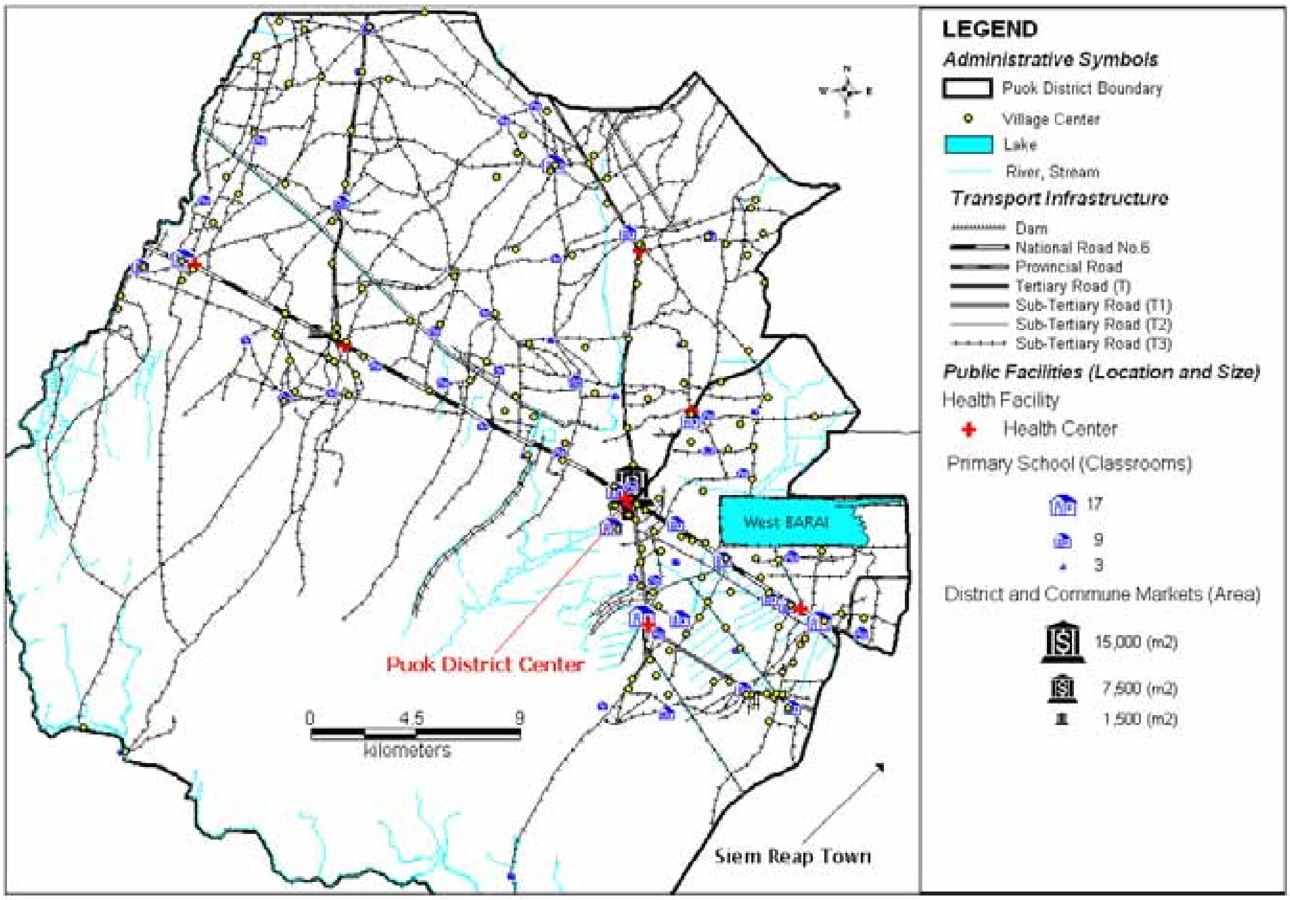


Figure 8: Road network and existing public facilities in Puok district

assumption) and with economic growth of 5%. The average unit travel costs of rural traveler on each road surface are calculated by weighting of shared transport modes in the district. The average weighted village traveler cost per km for each surface and road types c_{ij}^{s} are shown in Table 1.

Table 1: Average Village Traveler Cost per km c_{ij}^{s}

		Without Annual Economic Growth	With Annual Economic Growth of 5%
Road Type	Surface Type	Travel cost /km	Travel cost /km
National Road	Asphalt	\$0.0073	\$0.0116
Provincial Road	Bitumen	\$0.0077	\$0.0116
Rural Road	Bitumen	\$0.0077	\$0.0120
Provincial and Rural Roads	Good laterite road	\$0.0081	\$0.0124
	Good earth road	\$0.0086	\$0.0133

The unit cost of link improvement per km and year for each surface and road types CC_{ij}^{s} are illustrated in Table 2. Routine and periodic maintenance are included in the unit cost. Road structures such as bridges were assumed to be maintenance free during the 15 year analysis period. All costs are discounted using a discount rate of 12%. Furthermore, an overall standard conversion factor (SCF) for the economy was estimated, taking the ratio of value of exports and imports at border prices to their value at domestic prices. The “overall economy” SCF of 0.92 was applied to transport cost as these are principally derived from time and money spent by rural people. In conversion of project investment costs to economic prices, an overall SCF of 0.85 has been applied to all types of construction work. Table 3 summarizes the coefficient of new facility allocation cost α_d^F . It is assumed that all public facilities are to be constructed on public land owned by the government or local authority. Hence, land price is not included in the facility allocation cost. Table 4 shows the annual number of demand trips a_o^F in each village to visit public facilities.

Table 2: Unit cost of link improvement CC_{ij}^s

Provincial earth road/year/km	$910
Rural earth road/year/km	$474
Provincial laterite road/year/km	$1,109
Rural laterite road/year/km	$622
Provincial bitumen road/year/km	$2,604
Rural bitumen road/year/km	$1,622

Table 3: Coefficient of new facility allocation cost α_d^F

Facility type	Cost per trips
Health center	$0.4599
School	$0.0197
Market	$0.0014

Table 4: Number of round trips in each village to public facilities a_o^F

Health center =	number of total population in each village x 0.99 trips/capita/year
Primary school =	number of pupils in each village x 228 trips/pupil/year
Market =	number of households in each village x 146 trips/household/year

The result of this study demonstrates that the integrated models of facility location and network design can be solved to optimality despite of its complex formulation. The tradeoff between expenditures and investment budgets in Figure 9 illustrates that the integrated model (CFLNDP) is superior to other classic models including Shortest Path problem, Pure Network Design Problem (PNDP), and Pure Capacitated Facility Location Problem (PCFLP). The total and travel costs provided by the integrated model are lower than the costs given by the classic models. Furthermore, in order to observe the model behavior clearly, sensitivity analyses considering financial and spatial constraints are implemented throughout this study. The three constraints included in the analyses are budget constraints, restriction on maximum numbers of new allocated facilities (β^F) and limitation on maximum travel distances (D_{max}^F).

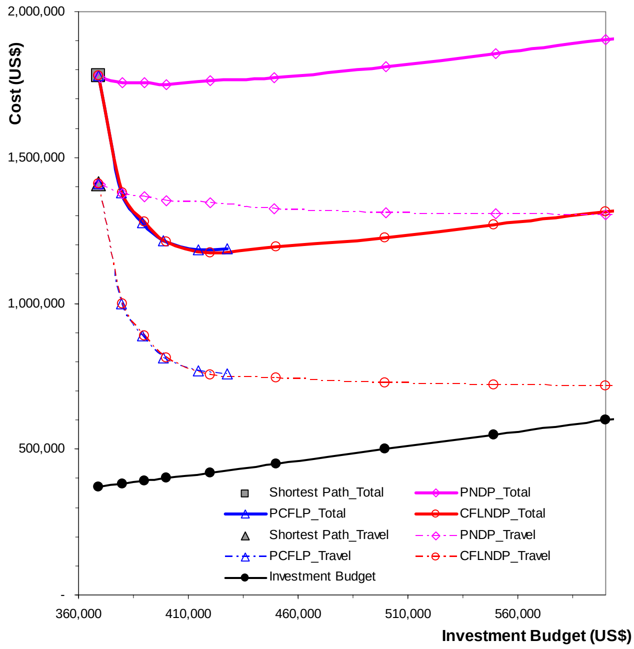


Figure 9: Comparison with other models

Different scenarios of investment budget sizes are to be tested within the model simulation. Figure 10 illustrates optimized Puok networks for an annual investment budget of US$462,000, US$480,000, US$600,000, and US$ 700,000. Budget of US$480,000 is the optimal budget which provides the least total cost. These Figures explain that the optimal network configurations change at different budget levels. Shown in the Figure10, the computational experiments with Puok network show that the model is in favor to build many small-scale facilities such as small-size school classrooms at different village nodes rather than constructing the big-scale ones at any village nodes. This result may due to the limitation of LP formulation in the paper. In order to optimize the total cost, there is no merit from constructing facility at one place and it will be better to allocate small facility at many places as it would minimize the travel cost. There is no scale

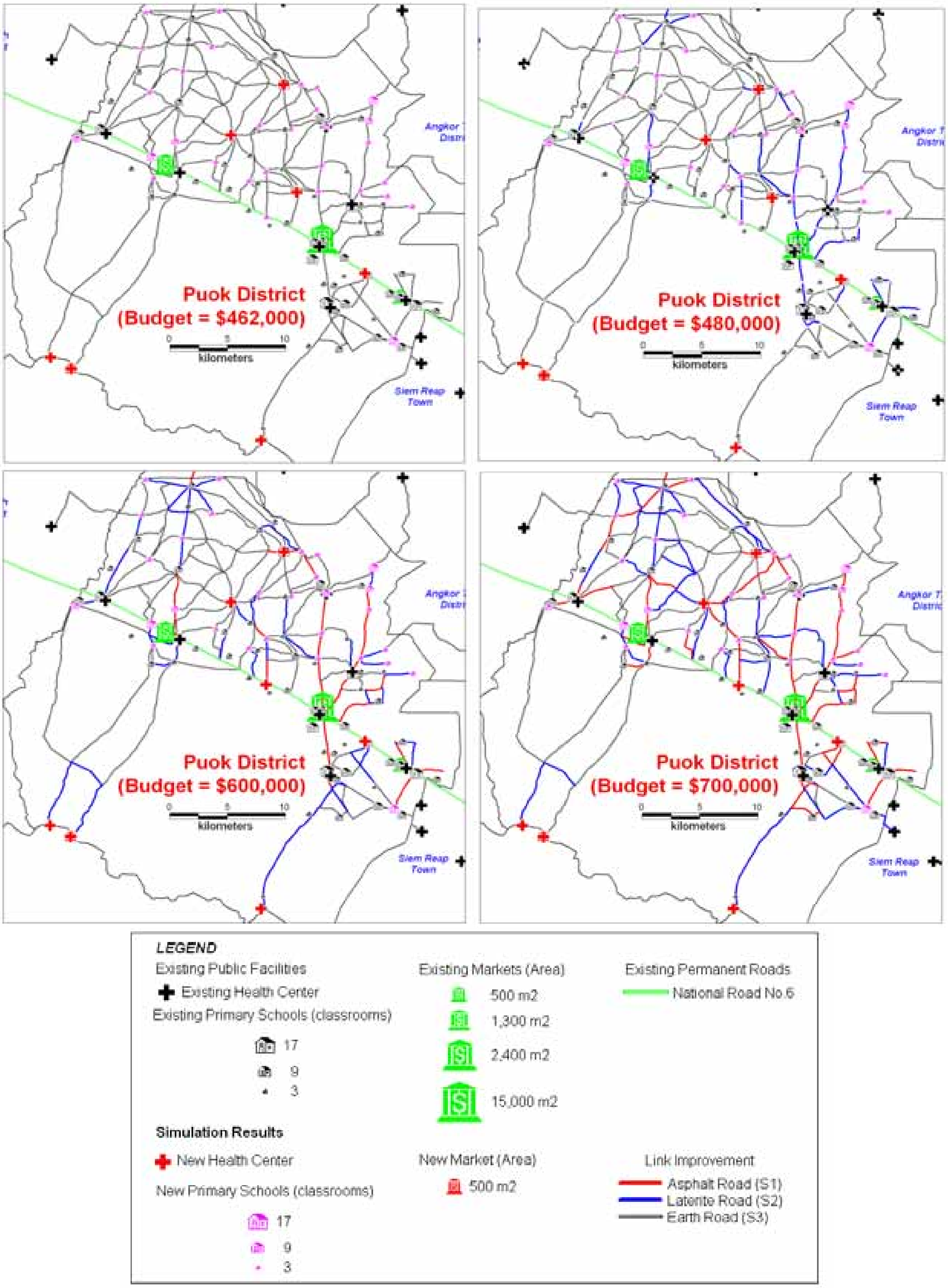
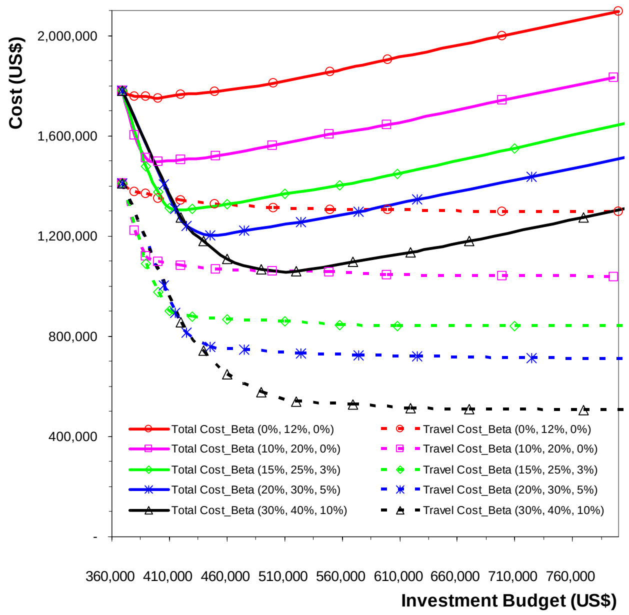


Figure 10: Optimal networks for budget = US\$462,000, US\$480,000, US\$600,000, and US\$700,000

effect as the unit cost of each facility used in the paper is proportional to the size of facility. On the other hand, although budget for infrastructure investments is sometimes available, public land and human resources availability may restrict number of new facility to be allocated. In the integrated model formulation, this constraint is represented by equation (7) where β^F representing percentage of new public facilities to be allocated (e.g. health centers, primary schools, markets). The result from this study shows that when the unit



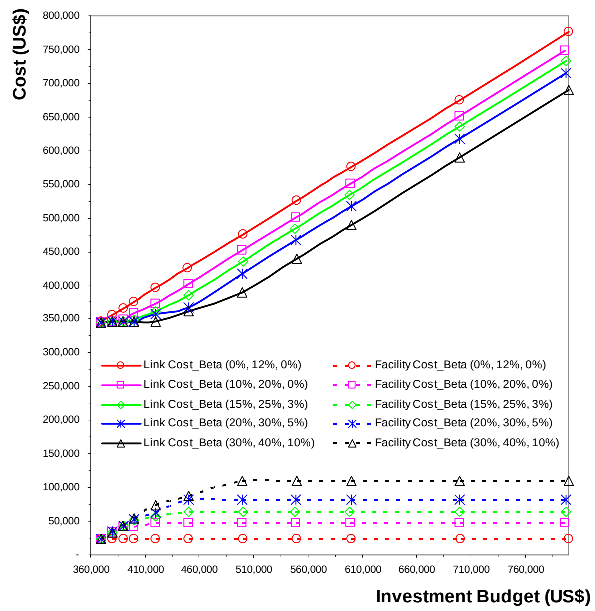


Figure 11: Total costs vs. travel costs for different β^F scenarios

Figure 12: Facility cost vs. link improvement cost for different β^F scenarios

facility cost is low, the more we increase the maximum number of new allocated facilities (β^F), the lower optimal total cost we obtain (Figure 11). This can be interpreted from the figure 12 that the integrated model tends to be Pure Facility Location Problem while available budget for link improvement is decreasing.

It may be vital to consider travel distance constraints to avoid biasing location of facilities to the populated areas which would penalize other isolated ones with low density. The transportation constraint circumscribes behavior by limiting the distances an individual can travel to reach each facility type. The value of an opportunity to an individual would decrease with distance because the amount of time that can be spent at the location decreases, and the monetary travel cost also increases. For a given time budget, the amount of time available to an individual for participating in activities decreases as travel time increases. This constraint was introduced to the integrated model by restricting the path flow variables $f_r^{F,od} \geq 0$ where the total travel distance to reach each facility is limited to a maximum desirable distance. If we include this constraint, the optimization process of the model is analyzed with limiting maximum allowed distances from village centers to public facilities locations.

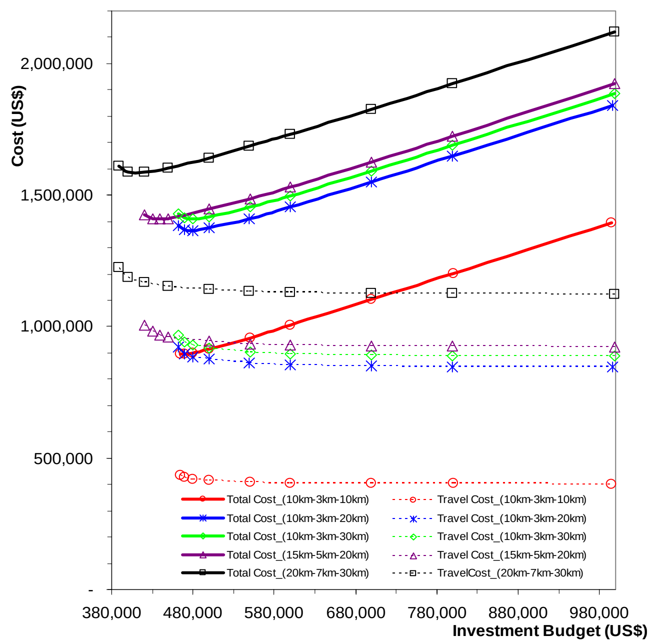


Figure 13 Comparison among travel distance options

The network is to be designed for the specified maximum permissible distance from a health centers, primary schools and markets. Then this would require allocating more new facilities. Clearly this constraint would contrast with the land use, policy, human resource, and economic constraints above. Hence, there are several options for decision maker. For example, either plan the new primary school in the areas or relax the maximum allowed distances from the primary schools. The transport planner can choose any options. Although the second option may reduce the expected education level in the area, it may be the only solution if the public land, human resources or investment budget is not available. As shown in Figure 13, a comparison among travel distance options considering minimum number of new allocated facilities is tried.

The travel and total costs are decreasing when we tighten the distance constraint. This result means that when more new facilities are needed to satisfy the constraint, link improvement becomes less beneficial. In other words, the road link upgrading with high quality level would contribute slightly to minimize the total cost unless numbers of new allocated facilities is restricted.

In the paper, a comparison between a conservative case and economic growth case is carried out. Table 5 explains a difference between the two cases. In conservative case, for β^F = (10%, 20%, 0%), the optimal solutions is reached by upgrading 14 road links with S2 level (Laterite road) whereas the other links is built with S3 level (Earth road). When β^F increase to β^F = (30%, 40%, 10%), only 2 links are paved with S2. It means that in this case the integrated model is more sensitive to the facility allocation rather than link improvement when we release the restriction of maximum number of new facilities. Conversely, in the 2nd case for bigger optimal budget sizes, 23 of 181 links for β^F = (10%, 20%, 0%) and 36 links for β^F = (30%, 40%, 10%) are improved with S2 level. This case means the sensitivity of the model in favorable of allocating facilities rather than link improvement is reduced as the difference between the improved link benefit and its cost becomes more significant. The sensitivity analysis clearly revealed that links improvement with superior levels is likely not affect the value of the objective function unless the improved link benefit is much bigger than its cost. The link variables in this model would contribute to affect the design decision unless there is a significant benefit of upgrading from one level to another level. Potential benefit of link improvement would include reducing transport costs and lower facility investments unless travel costs of each rural dweller are significant. And the travel costs depend mainly on their value of time. Moreover, for Puok network, we observed that the link variable does not tend to affect much the value of the objective function however an annual economic growth is considered. This reason may cause by high share of non-motorized transport in the district.

Table 5: A comparison of link improvement between conservative case and economic growth case

Case where cost parameters considering:	For β^F = (10%, 20%, 0%)	For β^F = (30%, 40%, 10%)
Without economic growth (conservative case)	Optimal budget size: US$390,000 Link variable: only 14 links are improved with S2 (Laterite Road)	Optimal budget size: US$420,000 Link variable: only 2 links are improved with S2 (Laterite Road)
With economic growth of 5% within 15-year period	Optimal budget size: US$400,000 Link variable: only 23 links are improved with S2 (Laterite Road)	Optimal budget size: US$450,000 Link variable: only 36 links are improved with S2 (Laterite Road)

Findings above are parallel to what is explained by Howe and Richards[6)] that rural poverty in most developing nations reduces the local demand for motorized transport to nearly zero and where there are only bicycle and animals to draw wheeled vehicles, the best-engineered paved road in the world will have little more merit than a basic earth road. But if rural productivity is high enough to generate effective household income to demand for mechanized transport and to increase their value of time, then the effect of transport cost reductions from road improvement with higher quality pavement may be important.

Another observation is that solutions to all problems above exist within time limit of 20 min. The integrated model is more difficult to solve to optimality than other classic models. The gap ratio between the feasible solution and its LP relaxation generated by the integrated model are much bigger than the ones provided by other models. These ratios increase with the number of new allocated facilities β^F.

The optimal budget depends on relative cost of link improvement and facility location when the optimal configuration of the road network is determined endogenously. It is important to determine realistic constraints (e.g. maximum total number of new facilities) and appropriate parameters (e.g. unit facility cost) for real model application.

6. Conclusions

In this research, we have studied the problem of designing an optimal rural road network to provide better access for the rural residents to reach public services. Throughout a budget sensitivity analysis to examine the model behavior, an effective process for optimizing the resource allocation to public infrastructures improvement is identified. Having defined a specific objective and a set of constraints, the formulated model can be solved to optimality by searching for an optimal combination value of the decision variables (link upgrading and facility allocation). The model demonstrates its applicability in a typical rural network of Cambodia. In rural areas with low population density in developing countries, investment in many small-size facilities distributed among villages along with provision of a good basic earth road seems to be the most cost-effective approach. Upgrading rural road with high engineered standards would not be more beneficial unless there is a considerable high rural productivity. The studied model is going to provide the decision makers with useful information at every stage of infrastructure investment to explore the validity and effectiveness of capital allocation.

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An Integrated Model for Optimizing Rural Road Network and Public Facility Locations in Developing Countries*

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In many developing countries, the poor geographical accessibility has made rural residents isolated from opportunities which improve quality of life. The objective of this study is to provide an integrated model for optimal road network and multi-type public facility location design considering budget constraint. The model is simulated with the real road network in Puok district, Cambodia. It is found that investment in many small size facilities distributed among villages along with a provision of a good basic earth road seems to be the most cost-effective approach in the study area.

発展途上国の地方部における道路網と公共施設立地の同時最適化モデルに関する研究*

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発展途上国の農村部においては、アクセシビリティの低さ故に住民が生活の質を向上させるための様々な機会を利用することができなくなっている。本研究は、途上国における道路網と公共施設の立地の同時最適化を達成するための統合モデルを開発している。本モデルは予算制約下において、道路舗装の種別と施設の種類を考慮し、最適な道路整備と公共施設の立地計画を支援しうるものである。本モデルをカンボジアの農村部に適用した結果、小規模な施設を砂利舗装道に沿って建設することが効率的であるという結果が得られた。