AN INTEGRATED MODEL OF RURAL INFRASTRUCTURE DESIGN IN DEVELOPING COUNTRIES

Salpiseth HENG
Graduate Student
Dept. of Architecture and Civil Eng.
Toyohashi University of Technology
1-1, Hibarigaoka, Tempaku-cho,
Toyohashi city, 441-8580 Japan
Tel: +81-532-44-5625
Fax: +81-532-44-6831
E-mail: heng_salpiseth@yahoo.com

Yasuhiro HIROBATA
Professor
Dept. of Architecture and Civil Eng.
Toyohashi University of Technology
1-1, Hibarigaoka, Tempaku-cho,
Toyohashi city, 441-8580 Japan
Tel: +81-532-44-6833
Fax: +81-532-44-6831
E-mail: hirobata@acserv.tutrp.tut.ac.jp

Hitomi NAKANISHI
Research Associate
Dept. of Architecture and Civil Eng.
Toyohashi University of Technology
1-1, Hibarigaoka, Tempaku-cho,
Toyohashi city, 441-8580 Japan
Tel: +81-532-44-6842
Fax: +81-532-44-6831
E-mail: nakanish@tutrp.tut.ac.jp

Abstract: In developing countries, poor geographical accessibility due to poor quality of roads and ineffective public facility locations has made a negative impact on rural residents’ welfare. The lack of proper planning of these public infrastructures is also a major problem. The objective of this study is to investigate an integrated model to design an optimal rural road network considering financial and spatial constraints. The rural road network and new multi public facility locations are to be optimally designed simultaneously to achieve least total cost spent by government and residents. Having defined a specific objective and a set of constraints, an optimal rural road network configuration is determined endogenously by searching for an optimal combination value of the decision variables. The model is going to provide the decision makers with useful information of the rural infrastructure investment to explore the validity and effectiveness of capital allocation through the sensitivity analyses.

Key Words: integrated model, rural infrastructure design, developing countries

1. INTRODUCTION

Despite a good rate of economic growth in many developing countries in the past decades, poverty in these countries is still largely a rural phenomenon with majority of the population concentrated in rural areas. These rural residents are not integrated into the mainstream of national life. They barely participate in the economic and social activities. One of the factors of their low quality of life is poor infrastructure development. Rural transport networks in such countries are underdeveloped and of poor quality. Approximately 900 million rural residents in the developing world can not access to roads and about one third of these people use only non-motorized transport (Lebo and Schelling, 2001). The accessibility and affordability of services for the rural people is related to weak communications and poor
transport infrastructure as there is a significant correlation between poverty and remoteness. Thus it is argued that rural road construction is a key to raising living standards in poor rural areas (Gannon and Liu, 1997). As agricultural output from rural areas is still a very significant component of the national economy in the developing nations, the rural transport systems require as much attention from transport planners as does inter-urban transport (Tolley and Turton, 1995). From another angle, it is clearly mentioned by Howe and Richards (1984) that providing peasants an adequate access to social services, such as medical and health services and advice, proper nutritional care for the young and education facilities, would determine to a large extent the improvement of social and economic welfare of the rural populace. These are also important determinants to ensure the continued self-sustaining momentum of the rural development efforts (Odoki et al., 2001). There is evidence that because of poor geographical accessibility, basic public services do not reach the majority of the population in these nations. Under this background, claims have also been made that by reducing isolation, better roads and optimal facility locations reduce vulnerability and dampen income variability. It is hard to disagree with the proposition that enhancing accessibility to various public facilities is important for the economic survival and the welfare of rural communities.

Apart from limited financial resources to build rural roads and public facilities, the lack of proper planning methodology of these rural infrastructures is also a major problem. Hence, a research on the planning of rural roads and public facility locations in a comprehensive integrated manner targeting optimized budget allocations has been strongly motivated to be carried out in this paper. Furthermore, 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. 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 (Daskin and Owen, 1999; Melkote and Daskin, 2001a). It would assist decision makers in developing countries on how to make a choice effectively under limited fund constraints to build schools, expand hospitals, or improve road links (Daskin and Owen, 1999). Therefore it is meaningful to investigate an integrated model where rural road networks are optimally designed considering existing and new multi public facility locations. In this study, existing rural road network and new multi public facility locations are to be optimally designed simultaneously to achieve minimum total cost comprising construction and operation cost spent by government/local authority and rural residents respectively. This paper would give some merits over previous similar research papers. With a different solution approach, several options of road surface (e.g. bituminous, laterite/gravel, and earth) and multi-type public facilities (e.g. health centers, primary schools, and rural markets) are considered in the studied model. Existing public facility locations and permanent roads are also taken into account throughout this research. In order to prove its applicability and validity, the proposed model is to be simulated with a real rural road network followed by sensitivity analyses considering financial and spatial constraints.

The remainder of the paper is organized as follows: section 2 reviews previous studies involving the planning of rural road networks and facility location models. Previous works on integrated models of network design and discrete locations are also presented. The model definition, assumption, and formulation are illustrated in section 3. Section 4 describes the study area to be challenged with the formulated model and concerns with application and validation of the proposed model. Solution method is described throughout the section. The
sensitivity analyses followed by computational results are also reported in this section. Finally, the conclusion and future directions are provided in section 5.

2. REVIEW ON PLANNING OF RURAL ROAD AND FACILITY LOCATIONS

Many reviews on merits of rural roads clearly prove that rural transport infrastructure is really vital for rural livelihood. In Figure 1, the rural road network is the lowest level of road network that connects the rural population, and therefore the majority of the poor, to their farms, local markets, and social services, such as schools and health centers, potentially increasing their real income and improving their quality of life. This road network was developed from cart tracks which were originally footpaths (Howe and Richards, 1984).

In recent years, there have been many studies focusing on planning of rural road network. Van de Walle (2002) worked on how to select rural road for investment focusing on the objective of poverty reduction by identifying places where poverty, inaccessibility and economic potential are high. Poverty-focused hybrid methods by using cost-benefit analysis and cost-effectiveness calculation were carried out within the paper. Another related line of research deals with rural roads, Shrestha (2003) had developed a computer-aided model for planning and prioritizing district transportation networks in Nepal. A computer model using GIS for planning district road network had been developed in this research. Two different models were proposed for developed and underdeveloped region respectively. Additionally, combination of the producer’s surplus and consumer’s surplus has been used as a methodology in this study. The prioritization of roads in the developed area is based on the economic net present value (ENPV), economic internal rate of return (EIRR) and the benefit cost ratio (B/C ratio); whereas socio-economic criteria is used for underdeveloped area, but it was supplemented with the economic analysis. A traffic simulation model was used by Athanasenas (1997) to evaluate rural road network design and alternative rural road investment strategies in the United States. An approach for cost-effective rural road management was identified by examining both deterministic and probabilistic traffic simulation models. Various methods for prioritizing rural roads investment using social, economic, strategic and technical criteria were identified in TRL (2003). There are seven prioritization procedures presented. These methods comprise Road Economic Decision (RED) model which is a simplified version of the complex Highway Development and Management (HDM). RED model is recommended for low traffic about 50-200 vehicles per day whereas HDM is suited to roads where access is reliable and traffic is high. The analyses compare the costs of road improvements with the time savings and lower vehicle operating costs on roads of reduced roughness. The second procedure Core Network establishes a core of roads within a bigger network and the core roads is to be highlighted on a network map. Socio-economic Benefit/Cost Analysis, the third procedure, is applicable for basic access standard on low volume roads where the benefits come from providing access rather than reducing vehicle
operating costs. Consultation, screening, technical analysis and consultation are the four step cycle of this procedure. The fourth procedure Integrated Rural Accessibility Planning is a local level planning tool to prioritize rural infrastructure investments by looking at access of the rural household to basic services and facilities such as health services, schools, market, and water supplies. This procedure is suitable for very low volume roads and village tracks. However, presently this method, which was developed in 1994 in Philippines by the International Labour Organization (IRAP, 2002), has been applied to many projects in developing countries in Asia such as Cambodia, Laos, Thailand, Philippines, Nepal, India, and Indonesia. The fifth procedure Cost Effectiveness Indicator using population as an indicator of the social impact of road improvement needs only little data collection. The sixth method is Point Scoring. In this method, the decision can be based upon social and economic indicators and points are getting from the benefits derived from improving the road. The roads with the highest points have high priority to be improved until funds are exhausted. The final procedure Activity Matrix ranks road investment by considering traffic volume. This method is used for road maintenance prioritization.

Nearly every public sector and private enterprise encounters decisions on locating its facilities as the performance of both sector facilities depends in part on the locations chosen for those facilities. Facility location models thus have attracted so much attention from academia and industry that it has been addressed extensively and intensively in the last decades. Although the mathematical formulations of locational analysis may be too sophisticated for applying in developing countries, several studies have proved the effectiveness of such models in the locational decision-making process to deal with planning of public facilities. Location-allocation problems deal with decisions of finding the best or optimal configuration for the installation of one or more facilities in order to attend the demand of a population. An approach to public facilities planning was exploited by the work of Yeh and Chow (1996). Responding to the constraint of available spatial data, an integrated GIS and location-allocation model was developed to find the best sites for public facilities. Application of location models in public sector has been examined by Marianov and Serra (2002). Formulations of covering and p-median model applied in public facility location were presented. Similarly, the public facility location models have been described widely by Hansen et al. (1983). Basic location models and its extensions were illustrated. Calvo and Marks (1973) involved with location of health care facilities by developing an analytical approach as an optimization model. Location-allocation models were also used by Rahman and Smith (1999) to design optimal locations of health facilities in a rural area in Bangladesh. As integer-programming problems, the formulation of these models considers the maximum allowable travel distance and number of facilities to be located. These models were later extensively reviewed by the same authors (Rahman and Smith, 2000). The objectives and merits of these models in planning rural health facilities location were broadly illustrated and discussed in the last paper. Another same work deal with application of location models, Kumar (2004) used location-allocation models to examine the changing geographic access to and locational efficiency of both basic public and private health care services in Indian districts. In a recent work by Daskin and Dean (2004), formulations of three classical facility location models, location set covering model, maximal covering location model and p-median model were broadly reviewed and considered as the key models for planning location of health care facility. Numerous applications of those models in health care were identified. Location analysis using location models is likely one of the most popular approaches to rural health facility location planning in developing countries. Although transportation network design and location theory had been studied in isolation of each other in the past, recently few investigations on developing models for integrating network design and facility location have
been studied. Cruz et al. (1999) worked on a multi-level network optimization problem. The model formulation integrating discrete facility location, topological network design and network dimensioning had been defined. Two close related papers of research written by Melkote and Daskin (2001a; 2001b) developed a formulation of the network design and outlined heuristic and optimal solution procedures. By generalizing the classical simple plant location problem, the integrated model of facility location and transportation network design was used to analyze the transportation planning scenarios. Sensitivity analysis for different cases has been conducted throughout the two papers to observe the performance of the integrated model.

There are evidences of the rich body of literature dedicated to the theoretical study of rural road network planning and location problems. Nevertheless, there are still very few studies investigating the network design with facility location in consideration. Moreover, those studies provided a limited application by simulating only on testing network. It was also concluded by Daskin and Owen (1999) that the interaction between the two areas is relatively unexplored. However, the above reviews of studying the optimal location of facilities in different spatial settings which is a very active research data, copious in ideas and challenges, would be a good concept for starting to formulate a complex model in this paper.

3. INTEGRATED MODEL OF RURAL INFRASTRUCTURE DESIGN

3.1 Model 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 2). 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. Figure 3 illustrates a rural road network comprising village nodes connected to each other by road links. Road links with dotted and continuous lines are existing tracks or roads in poor condition which can be upgraded to all-weather roads without land acquisition; 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 public facilities (health centers, primary schools and rural markets). The model aims to achieve least total cost which is a concept developed for utility planning that is being applied to transport. The total cost includes all costs associated with construction and operation of a road network over its entire life comprising all money spent by producers (local authority) and consumers (rural residents).

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.

3.2 Model Formulation

A planning agency, such as government, is assumed to be responsible for designing rural infrastructure including public facilities allocation and road improvement to support the economic survival and welfare of the rural residents. 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 set of facility types.
(F = (F₁, F₂, F₃) for health centers, primary schools and rural markets respectively). O, D are sets of demand and supply nodes respectively (O, D ⊆ N). K_{od} is set of paths connecting OD pair od. d_{ij} is link distance from the node i to node j. C_{od}^{d} is travel cost per unit flow on path r connecting OD pair od. C_{ij}^{d} is travel cost per unit flow and distance of traveling over surface type s on link (i,j). \alpha_{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} \cdot 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. \alpha_{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}^{f} equals 1 if link (i,j) is on path r between OD pair od, 0 otherwise. \beta^{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}^{f} = 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 \(\eta \in \mathbb{N}\).

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. Where should be locate public facilities? What size? Which road link should be upgraded to higher quality? Between spending on link improvement and allocating more public facilities, which one is the most cost-effective investment? If public facility allocation is more cost-effective than link improvement, which facility, for instance, among health centers, primary schools and rural markets, is the most cost-effective one?

The objective function of the integrated model aims to optimize the total cost as follows:

\[
\text{Minimize } \sum_{s=1}^{3} \sum_{(i,j) \in L} C_{ij}^{s} \cdot X_{ij}^{s} + \sum_{F=1}^{3} \sum_{d \in D} \alpha_{d}^{F} \cdot FC_{d}^{F} \cdot Y_{d}^{F} + \sum_{s=1}^{3} \sum_{(i,j) \in L, i<j} CC_{ij}^{s} \cdot X_{ij}^{s}
\]

However, as budget constraint is very important in this study, we should consider different scenarios of budget design problem. With an investment budget constraint, we design the infrastructure by keeping total transportation costs to a minimum. 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 solution time. 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 (Heng et al., 2006):
Minimize \[ \sum_{s=1}^{3} \sum_{i \in L} C^s_{ij} x^s_{ij} \] (2)

Subject to \[ \sum_{r \in K_{od}} f^{F,od}_{ri} = q^{F}_{rod} = y^{F}_{rod} a^F_{rod} \quad \forall (o,d) \in O,D, \forall F \in F \] (3)

\[ \sum_{s=1}^{3} x^s_{ij} = \sum_{F=1}^{3} \sum_{i \in O,D} \sum_{r \in K_{od}} f^{F,od}_{ri} \delta^s_{ijr} \quad \forall (i,j) \in L \] (4)

\[ \sum_{i \in L} x^s_{ij} = 1 \quad \forall i \in L, \forall s \in S \] (9)

\[ \sum_{d \in D} d EY^F_d \leq 0 \quad \forall F \in F \] (6)

\[ \sum_{s=1}^{3} X^s_{ij} = 1 \quad \forall (i,j) \in L \] (10)

\[ 0 \leq y^F_{rod} \leq 1 \quad \forall o,d \in O,D, \forall F \in F \] (13)

Eq. (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→j and j→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→j and j→i is 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: \[ y^F_{rod} + \sum_{k=1}^{3} y^F_{dk} \leq 1. \] If demand at village o is fully 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) \( y^F_{od} \leq y^F_{dd} \). Eq. (13) is constraint for demand assignment variables. Maximum traveling distance for residents to get services from each facility is considered in the model. \( D^F_{max} \) is a factor to impose restriction on the path flow variable \( f^{F,od}_{r} \) which affects the decision variable of customer assignment \( y^F_{od} \). It means 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 results in a constraint to facility decision variables \( Y^F_d \) where the facility should be located. 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 (Rahman and Smith, 1999; Rahman and Smith, 2000). 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.

Several aspects of the integrated model are worth noting. When $\beta^F = 0$ and all the network link is improved with $S3$ only: $X_{ij}^s = 1$, 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: $X_{ij}^f = 1$, 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. MODEL APPLICATION AND VALIDATION

4.1 Study Area

In order to prove the applicability and validity of the formulated model, this study simulates the integrated model on rural road network in Puok District of Cambodia by using real parameters.

Cambodia, a developing country with a size of 181,035 km$^2$, is located in Southeast Asia, on the Indochina peninsula (Figure 4). Comparing with its neighbors, Cambodia is a geographically compact country administratively composed of 20 provinces, 4 municipalities, 185 districts, 1,621 communes and 13,703 villages. About 85 percent of the Cambodia’s 14 million people in 2005, and more than 90 percent of the poor, live in rural areas with annual population growth of 2%. Cambodia’s poverty is rooted in its large agricultural sector, which has low productivity and low growth, but provides livelihood to the vast majority of the country’s population. Cambodia’s economy has recorded with high annual GDP growth of 7% and 5.1% of GDP growth per capita in 2005. Nevertheless, the impact on the proportion of the population living in poverty seems to have been small. The latest World Bank’s poverty assessment based on Cambodia Socio-Economic Surveys (CSES) conducted in 2003/2004 shows that 34.7% of Cambodia’s population live below the national poverty line in 2004. Clearly mentioned in Cambodia Millennium Development Goal 2005, it needs to focus on poverty reduction in the rural less accessible areas as the surveys show that the proportion of the people below poverty line account for 45.6% compared with 28% for the urban and accessible areas (Ministry of Planning, 2005; World Development
Indicators, 2006). This would reflect on inequality and disparity between urban and rural sectors.

Economic development and improvement in living standards in rural Cambodia are seriously hindered by the poor state of roads and access and economic infrastructure. Inadequate transport infrastructure imposes higher costs and delays on travel, raising the costs of marketing goods or obtaining inputs, and limiting access to facility-based health and education services. According to the Ministry of Public Work and Transport, the total Cambodia Road Network covers about 40,000 km of both paved and unpaved roads, consisting of 4,802 km of national roads (both primary and secondary), 6,705 km of provincial roads and 28,000 km of tertiary or rural roads. The 28,000 km of rural roads defined as the roads with low traffic volumes, low geometric and construction standards, and passing through rural areas are in poor condition. These roads serve as feeders, linking villages with one another as well as with the nearest provincial roads, National Highway and market centers or towns. Although there has been considerable investment in rural road improvements, maintenance and coverage are major challenges.

Puok district with nearly 130,000 inhabitants in 2005 and where its center is located about 15 km from Angkor Wat Temple, has the largest residents among the twelve districts in Siem Reab province of Cambodia (Figure 5). With approximately area of 1,090 km², there are 16 communes and 154 villages in Puok district. As shown in the Figure 5, there are 61 primary schools, 7 health centers and 1 district and 3 commune markets distributed within the district. In Puok district, traveling outside the village takes a long time even if villagers own a bicycle or motorbike. This is due to the poor quality of roads, especially in the wet season. Except national roads, approximately 88% of the total road mostly rural roads are only dry-weather roads. This would harm the living condition of Puok residents, especially the ones living far from main roads during the rainy season, due to isolation from public services. Because of the bad road condition, rural families face a considerable transport burden by spending more time on traveling in the wet season and some areas are even isolated because of impassable roads. According to Accessibility Action Plan of Puok district in 2004, Pupils spend about 21 min and US$0.14 to reach the nearest primary school. Puok inhabitants have to travel in average approximately 30 min and it costs about US$0.4 to reach the nearest health center during wet season. The density of markets in the district is low and the average distance to markets for residents is long. The rural residents visit the nearest local market with an average travel time of 45 min and travel cost of US$0.6. Inadequate transportation and public facilities, especially in the remote areas of Puok district, has serious impacts on the lives and welfare of the majority of the population in the district. Addition to poor transport infrastructure within the district, lacking of motorized transport makes the Puok residents especially the poor more isolated from public facilities. It is clearly seen that non-motorized transport means, bicycle and ox-cart, are mostly used by Puok residents, particularly by the people living far from district center and national road. The closer the village is to the district center and Siem Reap Town, the more number of motorized vehicles, mostly motorbike, owned by residents in the village increase.

4.2 Sensitivity Analyses

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 (Heng et al., 2006). 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.

The proposed model in this paper is to incorporate facility locations in the decision-making process involved in the design of a rural road network. 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 6 illustrates that the integrated model (CFLNDP) is superior to other classic models as its total and travel costs are lower than the costs given by the classic models.

Moreover, in order to observe the model behavior, sensitivity analyses considering financial and spatial constraints are made throughout the study. They are budget constraints, restriction on maximum numbers of new allocated facilities \( (\beta) \) and limitation on maximum travel distances \( (D_{\text{max}}) \). Figure 7 and 8 illustrate an optimized Puok network for an annual investment budget of US$480,000 and
US$600,000 respectively. These Figures explain that the optimal network configurations change at different budget levels.

Although budget for public infrastructure investment is sometimes available, public land and human resources availability may restrict number of new facility to be allocated. In the model formulation, this constraint is defined by equation 6:

\[
\sum_{d \in D} FC_d^F Y_d^F - \beta^F \sum_{d \in D} EY_d^F \leq 0
\]

where \(\beta^F\) representing percentage of new public facilities to be allocated (e.g. health centers, primary schools, markets). The value of \(\beta^F\) is influenced by many factors. The maximum number of new allocated facilities may also depend on national policy. For instance, the government may give high priority to improve basic education and health care service rather than investing in building more local markets. In addition, lack of health care personnel(such as physicians and nurses), especially in developing countries, would impose a restriction on allocation of new health center. It may be not possible to allocate new classrooms of primary school if there is no teacher available. Furthermore, designing local markets depend on many criteria.

Annual turnover growth of agricultural products would answer to the need of new market location as these markets play a key role in improving agricultural marketing (Tracey-White, 2003). The investment in market facility also depends on the market users’ need (communities, producers and traders). Therefore, allocating new markets or improving existing market size may be determined by potential supply and demand for agricultural products and goods affected by local population and income growth. The result from this study shows that when the unit facility cost is low, the more we increase the maximum number of new allocated facilities \(\beta^F\), the lower optimal total cost we obtain. This can be interpreted that the integrated model tends to be Pure Facility Location Problem while available budget for link improvement is decreasing.

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. The optimal budget depends on relative cost of link improvement and facility location when the optimal configuration of the road network is determined endogenously.
5. CONCLUSIONS

In developing countries, among the development of agriculture, industry, electricity power and above all, the provision of an adequate rural transportation system are one of the basic needs. Rural infrastructures including road network and public facilities are recognized as necessary ingredients for rural development. In this paper, we have studied the problem of designing an optimal rural public infrastructure to provide better services to the rural residents. Throughout sensitivity analyses, 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. Improving rural road with high quality standards would not be more beneficial unless there is a high rural productivity. The model is going to provide the decision makers with useful information of the rural infrastructure investment to explore the validity and effectiveness of capital allocation. However, it is necessary to determine realistic constraints (e.g. maximum total number of new facilities) and appropriate parameters (e.g. unit facility cost) for real model application.

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