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Development of Infrastructure Maintenance Map based on GIS Data for Efficient Budget Management

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Abstract: Many developed countries, including Korea, are rapidly aged owing to years of use. Infrastructures such as roads, water, and sewage are Social Overhead Capital (SOC), which provide convenience to the nation and support national economic growth. Thus, continuous maintenance and investment are required because infrastructure deterioration is directly related to social effects, such as quality of life and safety. In addition, because infrastructure maintenance costs a lot of the budget, it is necessary to appropriate criteria for budget allocation, given assessing the condition of infrastructure. This study developed an Infrastructure Maintenance Map (IMM) based on a Geographic Information System (GIS) for infrastructure maintenance budgets and investment priorities. The IMM uses maintenance information for roads, bridges, water, and sewage, obtained from Bridge Management System (BMS), Pavement Management System (PMS) and facility data in South Korea. The IMM can calculate deterioration levels and maintenance costs of infrastructure repair methods. Maintenance priorities are also evaluated based on Multi-Attribute Utility Theory using the deterioration level, economic feasibility, and effect of facilities. This study contributes to easy decision-making regarding infrastructure investment priorities and maintenance budgeting to the status of facility on the 3D map by IMM.

Key words: Infrastructure Maintenance Map, Multi-Attribute Utility Theory, Budget Allocation, Maintenance Cost, Maintenance Prioirty

1. INTRODUCTION

Infrastructure is a major driver of national economic growth by increasing production efficiency in social infrastructure industries such as energy and logistics. In particular, infrastructure, such as roads, bridges, and water and sewage systems, play a role in supporting the national economy and increasing convenience to nations. However, considering the infrastructure size and the number of users, an aging infrastructure is a social potential risk. Thus, the need for infrastructure maintenance is increasing because of aging and reaching the end of their lifespan such as roads, bridges, ports, airports, water supplies, and sewage systems. An aging infrastructure can cause various social and economic problems, and responding to these problems is an urgent task [1].

Aging infrastructures can lead to safety issues. As infrastructure ages, corrodes or becomes damaged, there is a greater risk of accidents, which can result in casualties and property damage. In addition, safety issues in infrastructure facilities are becoming increasingly important because of climate change and the frequent occurrence of natural disasters. Then, a problem of economic inefficiency due to aging infrastructures. The poor condition of infrastructure increases the operation and maintenance costs, which can reduce business productivity and limit economic development. Additionally, an aging infrastructure can lead to side effects such as traffic congestion, increased energy consumption, and environmental pollution. consequential, the need for maintenance owing to aging infrastructure is gradually increasing, and an active response to this is necessary.

In the United States, the need to respond to the aging of infrastructure has increased since the 1980s, but infrastructure is seriously deteriorating because of investment delays. According to the American Civil Engineering Society (ASCE), the overall infrastructure grade is C-, indicating signs of overall deterioration. Accordingly, the President Biden administration announced the $2.25 trillion "Infrastructure Plan" for national infrastructure reconstruction in 2021 and decided to invest in improving roads and bridges [2]. Japan established a five-year plan to invest 15 trillion yen in disaster prevention and mitigation measures in 2020. This plan classified bridges into 'long-term lifespan measures' and 'bridge improvement targets,' and introduced asset management methods. The concept of asset management methods is to evaluate and optimize the impact of traffic congestion caused by improvement work and the cost of investment in construction [3]. The UK established the Infrastructure and Projects Authority (IPA) in 2016 and plans to invest £600 billion in infrastructure by 2028. Singapore has a world-class infrastructure with the highest national competitiveness; however, it continues to invest in infrastructure and recognizes its importance. Germany announced the Federal Transport Infrastructure Plan 2030 (FTIP) to establish investment priorities in infrastructure in the transportation sector and determine investment priorities according to the deterioration of roads, the need for maintenance, and future traffic volume [4]. Thus, the need for investment in aging infrastructure is challenge facing increasing worldwide.

Korea can't be an exception to this issue. Korea's major infrastructure was constructed intensively in the 1970s. Recently, facilities that are difficult to use have increased rapidly owing to loss of function or aging. The aging rate of medium and large-size infrastructure for more than 30 years is very high: 45% for dams, 37% for railroads, and 23% for ports [5]. In order to manage aging infrastructure, the Framework Act on Sustainable Infrastructure Management was enacted in 2018, and the Comprehensive Measures to Enhance Sustainable Infrastructure Safety (2019) were announced.

Therefore, this study developed an Infrastructure Maintenance Map (IMM), which is a system to evaluate the conditions of facilities and calculate the budget required and allocation to improve them for maintenance. The target facilities were selected as roads, bridges, water supplies, and sewage systems that are close to nations' lives. Then, the spatial scope was decided to be Goyang in Korea, so facility data in Goyang was collected.

2. DEVELOPMENT OF INFRASTRUCTURE MAINTENANCE MAP

2.1. Research Process

The research process for the IMM development is illustrated in Figure 1. The authors establish an IMM DB using facility data and calculate the deterioration rate to determine the facility grade. In addition, the IMM DB's maintenance volume is calculated and each data is applied to the multi-attribute utility theory. Based on this, the priority for facility maintenance and budget allocation is determined. In Korea, budget establishment, organization, and management are conducted respectively because the maintenance organizations of each facility differ. For this reason, the urgency and effect between heterogeneous facilities were considered to efficiently the budget allocation.

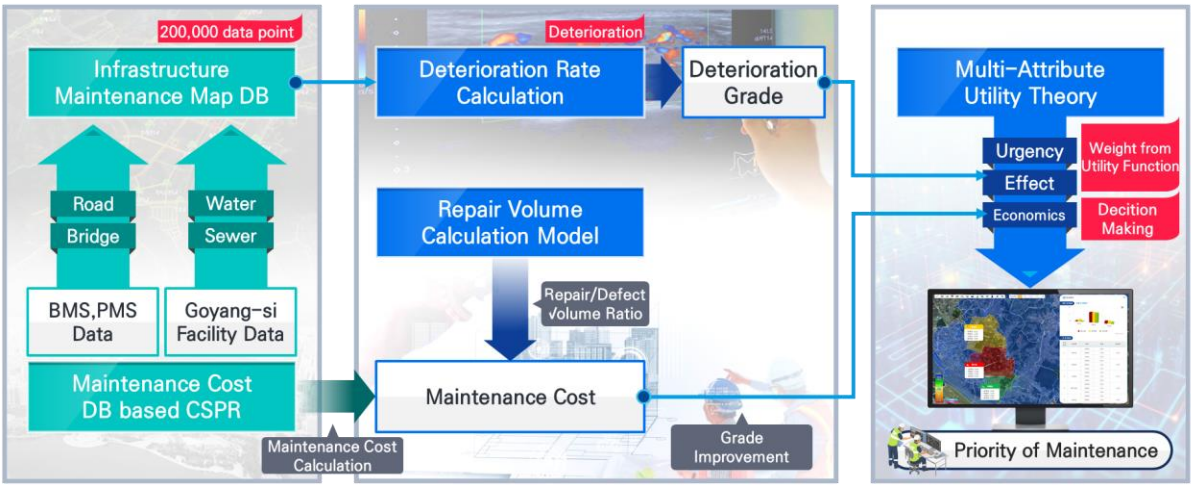


Figure 1. Research process of IMM development

2.2. Data Collection

The IMM visualizes the deterioration of facilities on a map based on spatial data about infrastructure facilities, such as roads, bridges, water supplies, and sewage. To develop an IMM, basic information such as the completion year and location of each facility, as well as safety-related information on aging and repair history, are required.

The authors 94,050 GIS data points were collected in cooperation with Goyan-si. Additionally, data from the Pavement Management System and Bridge Management System managed by the Korea Institute of Civil Engineering and Building Technology were used to inspect the safety history of roads and bridges. A precision safety diagnosis report managed by the Korea Authority of Land and Infrastructure Safety was collected and used for the water supply and sewage systems. To calculate the maintenance cost of the facility, the types of representative damage for each facility were derived, and the maintenance method for each damage was mapped. By applying the Construction Standard Production Rate, which is the standard for calculating costs in Korea, to each maintenance method, the maintenance cost per unit was constructed as a database.

2.2. Deterioration Rate Calculation

Although the data of the facility were collected as much as possible, safety grades for some facilities were missing or omitted. To solve this problem, an aging algorithm was developed that can calculate the deterioration rate according to the current state and environment of the facility. A graph of the aging score is shown according to the persistent period of the facility and the number of years used; the current grade is predicted based on this. If there was a safety grade for the facility, that grade was used; if there was no data, the grade obtained through the aging algorithm was used.

$$y = 6 - e^{\frac{ln5}{n}x} \quad (1)$$

where y is the deterioration rate, n is the persistent period of the facility, x is the number of years.

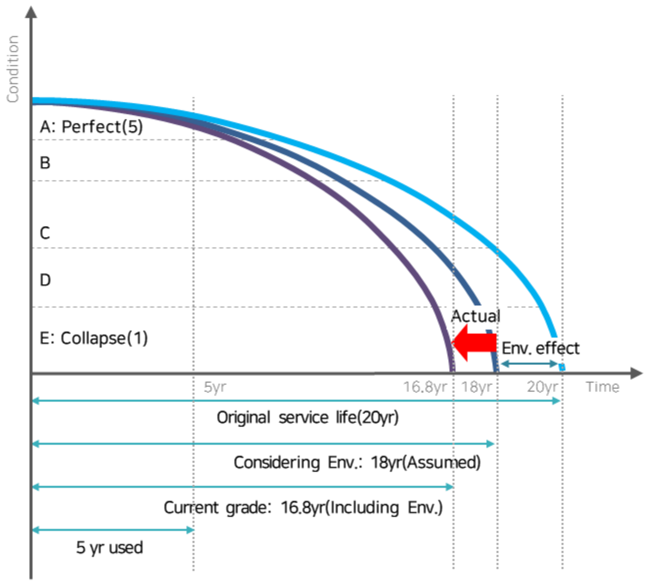


Figure 2. Deterioration rate curve

2.3. Multi-Attribute Utility Theory

In this study, the Multi-Attribute Utility Theory (MAUT) is applied to evaluate investment priorities among heterogeneous facilities. MAUT solves decision-making problems based on various criteria by objectifying and quantifying subjective and qualitative evaluations as Analytic Hierarchy Process (AHP) techniques [5]. This technique is useful for gaining insights into complex decision-making processes by dividing the utility model into multiple attributes and evaluating them based on multiple criteria to calculate the utility of alternatives. The utility equation derivation process consists of ① identifying attributes, ② quantifying attribute levels, ③ deriving single-attribute utility functions, ④ evaluating the importance of attributes, and ⑤ constructing multiattribute utility functions. Urgency, effect, and economics were determined as attributes for deriving priorities for each facility, through an expert advisory meeting. Detailed definitions and factors for each attribute are shown in Table 1.

Table 1. Attributes and factors of MAU

Attributes	Description	Factors
Urgency	The extent to which maintenance is urgently needed as infrastructure ages and performance deteriorates	Grade or deterioration Number of reported complaints
Effect	Degree of direct and indirect damage to surrounding users and other infrastructure in the event of infrastructure damage	Geographical characteristics Effect on surrondings
Economics	Cost-effectiveness required to improve infrastructure performance	Cost for infrastructure maintenance Grade Improvement

In the attribute identification stage, the individual attributes that determine maintenance priorities are derived. In the attribute level quantification stage, the evaluation ranges (maximum and minimum) of the identified attributes are determined. In the single-attribute utility function derivation stage, the utility function for each attribute is derived according to the quantified attribute level, and linear and exponential functions are generally used. In the attribute importance evaluation stage, the relative importance of individual attributes is determined and the AHP technique is generally used. In the multiattribute utility function construction stage, a function is derived that represents the contribution of each attribute to the maintenance priority calculation. The multi-attribute and single-attribute utility equations are as follows:

$$U = \sum_{i=1}^{n}(k_i \cdot u_i) \tag{2}$$

where U is the multi-attribute utility, k_i is the weight of attributes, u_i represents attributes (urgency, effect, and economics).

$$u_n = a(x_n)^2 + bx_n + c \tag{3}$$

where u_n is the single-attribute utility and x_n is the sum of factors by attributes (n=1 is urgency, n=2 is effect, and n=3 is economics).

$$x_n = \sum_{i,j=1}^{n}(k_{ij} \cdot x_{ij}) \tag{4}$$

where, k_{ij} is weight of factors, x_{ij} is factors by attributes, only economics has ($x_{31} \div x_{32}$).

The priority calculation algorithm of the IMM analyzes the attributes that commonly affect the maintenance priorities of different facilities through an expert survey. The criteria for budget allocation by facility according to the total utility were presented by defining the utility of facility maintenance as urgency (grade or deterioration, complaints), effect (geographical characteristics, effect on surroundings), and economics (cost of infrastructure maintenance, grade improvement) (Figure 3). A survey was conducted with nine public servants and ten experts in charge of facility maintenance to quantify the utility coefficient for each attribute.

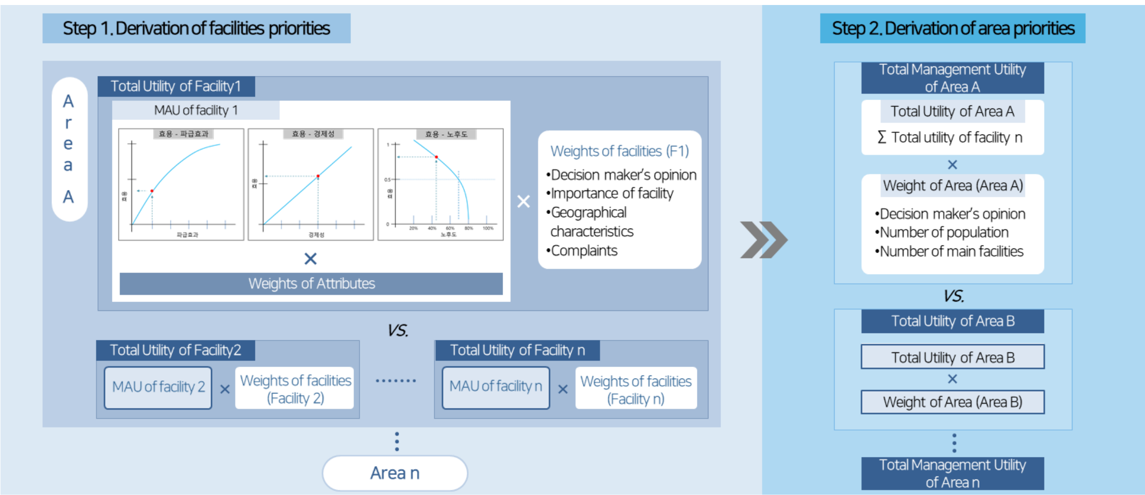


Figure 3. Process of MAUT application

By applying the collected data to the MAUT, the utility of each facility was first derived for IMM development, and then the weight was calculated to determine the maintenance priority between facilities. Because the IMM's ultimate goal is to provide information for determining the budget allocation and maintenance priorities between facilities and regions. The decision-makers' judgment criteria are required if multiple facilities have the same utility value. Accordingly, a survey was conducted with nine public servants in charge of facility maintenance, and an AHP analysis was conducted.

Priorities were calculated by multiplying individual utility values and weights according to facilities, and as a result, priorities were determined in the order of road-bridge-water supply-sewage. Similarly, the importance of the population density and traffic volume was calculated to determine the priority of the region, which was divided into 10 grades and expressed as scores. The scores were distributed according to the population density and traffic volume for all areas of Goyang-si. All facilities and regions in Goyang had utility values and weights and were used to develop the IMM system.

3. INFRASTRUCTURE MAINTENANCE MAP

3.1. Characteristics of Infrastructure Maintenance Map

This system is equipped with an investment priority algorithm based on MAUT to manage not only facility maintenance but also support decision-making regarding budget allocations. An infrastructure maintenance map system was constructed based on Goyang data collected through MAUT. To derive the priority of facilities in each region, a grid of Goyang units of [1 km × 1 km] was constructed. This is because when the priority is derived for each facility unit, the difference in the quantity of each facility is very large, so a minimum standard for decision-making is required. It is possible to search for aging by region and facility on the map, and the aging of roads, bridges, water, and sewage is expressed in three stages (Good: Green, Normal: Yellow, Bad: Red) according to the percentage of grade (Figure 4).

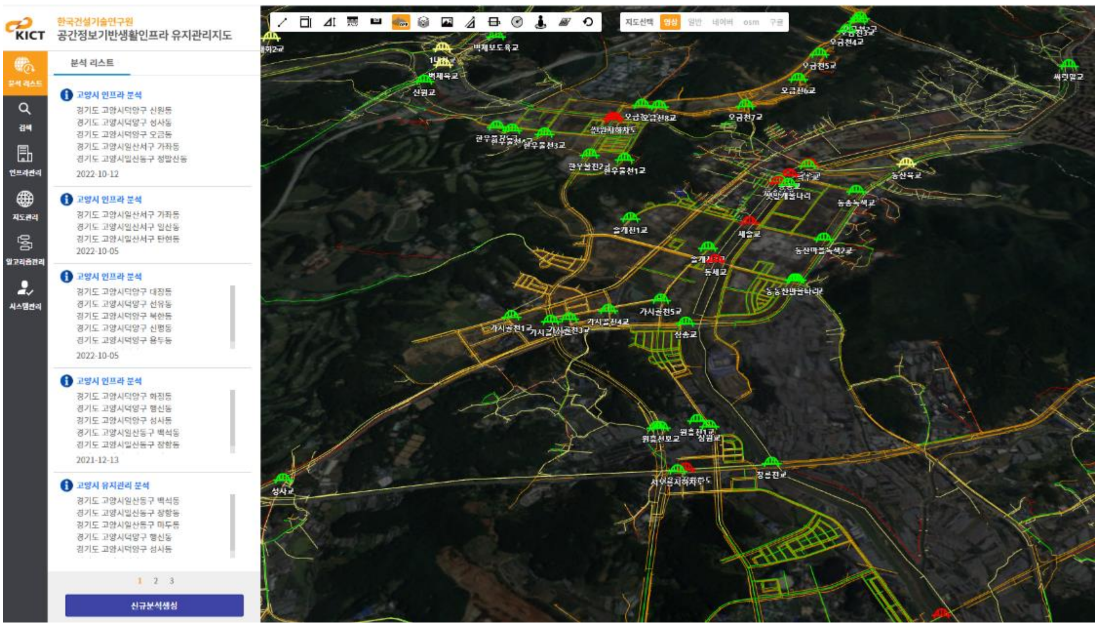
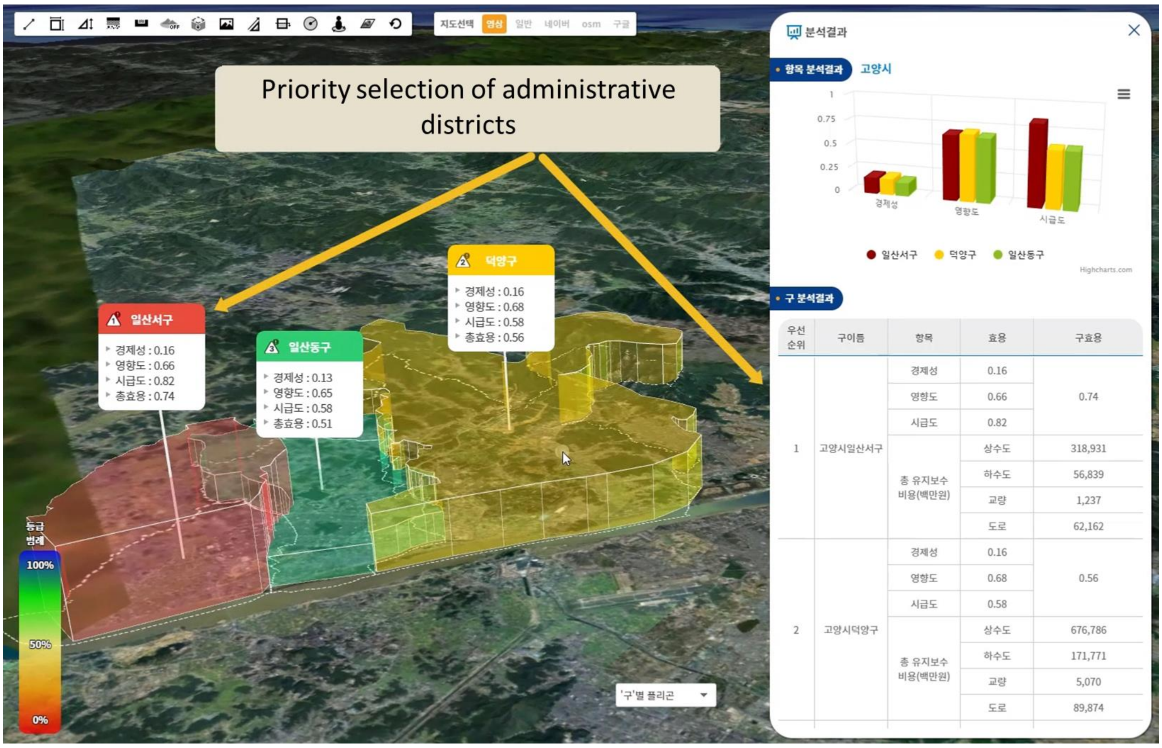


Figure 4. Visible deterioration of facilities

In addition, the IMM visually expresses the utility values, effects, and economics of the selected grid or administrative district (Figure 5). When grid a is selected, the average value and total utility of all facilities in the grid can be used to determine the priorities through a comparative analysis. When an administrative district was selected, the average data rate, maintenance volume, and total maintenance cost for each facility could be determined. The Korean administrative system is composed of several Gu in one city. When the A-Gu is selected, the maintenance volume and cost of all facilities included in the A-Gu and MAU-based priorities for each facility can be identified. It is also possible to determine Gu's priorities through the total utility. Through this IMM, the facility manager can determine the priority for safety inspection of the facility and perform preemptive maintenance management, and the budget allocation decision-maker can efficiently allocate the budget through budget and utility priorities.



우선 순위	구이름	항목	효용	구효용
1	고양시일산서구	경제성	0.16	0.74
		영향도	0.66	
		시급도	0.82	
		총 유지보수 비용(백만원)	상수도	318,931
			하수도	56,839
			교량	1,237
			도로	62,162
2	고양시덕양구	경제성	0.16	0.56
		영향도	0.68	
		시급도	0.58	
		총 유지보수 비용(백만원)	상수도	676,786
			하수도	171,771
			교량	5,070
			도로	89,874

Figure 5. Analysis of maintenance cost

3.2. Application of Infrastructure Maintenance Map

According to the analysis results of the IMM, in Goyang, the priority of maintenance appeared in the order of Ilsanseo-gu > Deokyang-gu > Ilsandong-gu. By facility, the costs were in the order of water supply > sewage > roads > bridges. The budget required for the maintenance of roads, bridges, water supply, and sewage in Goyang is approximately 1.8 trillion won, and considering indirect and general management costs, it is expected to be approximately 2.7 trillion won. Contrastingly, the Goyang 2023 infrastructure maintenance budget was confirmed to be 90 billion won for roads, 90 billion won for water supply, and 120 billion won for sewage, for a total of approximately 300 billion won. The budget required for infrastructure maintenance was approximately nine times different. Although not all maintenance work can be done in one year, it is necessary to allocate the budget efficiently according to the analysis results of the IMM because the aging infrastructure is expected to increase in the future.

4. CONCLUSION

The government's fiscal balance is expected to continue to decline at the same time as the proportion of aging infrastructure increases worldwide. In local governments in Korea, the scale of infrastructure management is steadily increasing, budgets and manpower remain at low levels, and financial independence is gradually decreasing. The financing plan for infrastructure management is planned around budget investment. There is a high concern that the burden on the national budget will increase due to maintenance costs that will increase rapidly due to climate change and aging in the future. It is necessary to prepare a plan to respond appropriately to the growing maintenance demand in the long run, alleviate financial burdens, and improve the level of maintenance to ensure the safety of people. That’s why the infrastructure maintenance map was developed to help make decisions in calculating maintenance and budget allocation priorities according to the conditions and utility of the facility. This map can be used to efficiently allocate the budget of local governments in the domestic infrastructure maintenance market and is expected to support preemptive maintenance through integrated facility management.

In future studies, the demand will be predicted by considering population changes, and infrastructure evaluation techniques tailored to local governments will be developed according to the budget size and regional characteristics of each local government. Furthermore, this map can be used to establish infrastructure-grade information and support policies.

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