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ENVIRONMENTAL LOAD ESTIMATING MODEL FOR NATM TUNNEL USING CASE BASED REASONING IN THE PLANNING STAGE OF TUNNEL CONSTRUCTION

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Abstract

Energy and resource consumption in construction projects is one of major causes to global warming. In order to evaluate the environmental load of construction projects, previous approaches calculated the quantities of construction materials and energy consumption from the use of equipment based on detailed design information after the completion of design. As a result, it is difficult to estimate environmental loads prior to design completion. This study is to develop an estimating model which can assess environmental loads for tunnel construction based on information available at the planning stage utilizing a case based reasoning approach. To validate the developed model, 10 verification cases were evaluated. The result showed that the mean absolute error rate (MAER) and the standard deviation (SD) of the proposed model were 8.9% and 6.0%, respectively, while the basic unit method were 21.4% and 12.9%, respectively. These results demonstrate that the proposed model is more accurate and more reliable than the basic unit method. The proposed model is expected to be a useful tool in reviewing environmental impacts of design alternatives and ensuring an environment-friendly design at the early stage of the project.

Key words: case based reasoning, environmental load, estimating model, tunnel

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1. Introduction

1.1. Backgrounds

In accordance with Article 42, 'Framework Act on Carbon, Green Growth' enacted in 2009, the South Korean government has been implementing various policies including 'Energy target management system' and 'Emissions trading scheme for reduction of greenhouse gases'. In recent years, the South Korean government finalized its 2030 target of reducing greenhouse gas emissions by 37 percent from Business-As-Usual (BAU) levels in order to show the international community its intention to actively respond to climate change. Greenhouse gases resulting from increasing energy and resource consumption due to global economic growth are a major cause of climate change, and various environmental policies are thus being implemented to reduce greenhouse gases. In the construction industry, many attempts to ensure environment-friendly construction have been made to meet the need for sustainable development (Huang et al., 2000; Onofrei et al., 2018).

Life Cycle Assessment (LCA) is one of the tools used to assess and control the environmental impact (Imura, 2011; Verbitsky and Pushkar, 2018). Domestic and international academic societies are using LCA to carry out studies on reduction of

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environmental load in the construction field. Many researchers have conducted mainly related to the studies quantifying environmental loads for buildings and infrastructures in the life-cycle and comparing environmental loads by materials and the methods of construction. The previous studies show that existing methods are allowed to assess environmental loads based on detailed design information after the completion of design. Thus it will be difficult to estimate environmental loads prior to design completion. The environmental load must be assessed during the initial stage of the project, in which various design alternatives are reviewed because the probability of improvement of environmental impact decrease toward the end of design (Comanita et al., 2018; van Geldermalsen et al., 2004).

Therefore this study was conducted to develop a model which can estimate environmental loads rapidly based on information available in planning stage of project. Two methods were used to develop a model. The first method, LCA, assesses the environmental loads from the construction materials and the energy consumption that were used in construction. The second method, Case Based Reasoning (CBR), estimates the project data of a test case based on the characteristics in a similar case that were extracted from the database (Doğan et al., 2008).

In this study, a tunnel that was constructed using the New Austrian Tunnelling Method (NATM) was evaluated. In South Korea, numerous tunnels have been built and new tunnels are planned because of the mountainous topography of South Korea (Min et al., 2008) and NATM method is the most commonly used the construction method for tunnel. Thus it is easy to collect a large number of design cases for constructing the case database (DB) to use the CBR methodology. In addition, the growing requirement of sustainable construction as well as an increasing demand for underground space, infrastructure and facilities necessitates detailed knowledge of pollutant emissions from tunnelling (Huang et al., 2015).

The effects of a tunnel on the natural environment, the man-made environment and on humans are caused by either chemical or physical impacts. The chemical impacts on the environment are caused by emissions of various kinds and the seriousness of the impact is dependent of the existing environmental quality (van Geldermalsen et al., 2004). Tunnelling almost inevitably consumes resources with corresponding environmental impacts (Huang et al., 2015).

1.2. Study methods and scope

Fig. 1 shows the processes used throughout this study. First, to build an environmental load estimating model using CBR, data on the designs of the previous NATM tunnel projects were collected, including design report, bill of quantities (BOQ), statement of construction cost, unit price list, etc. The collected data were used to build a case DB of the environmental load and attribute information for each project.

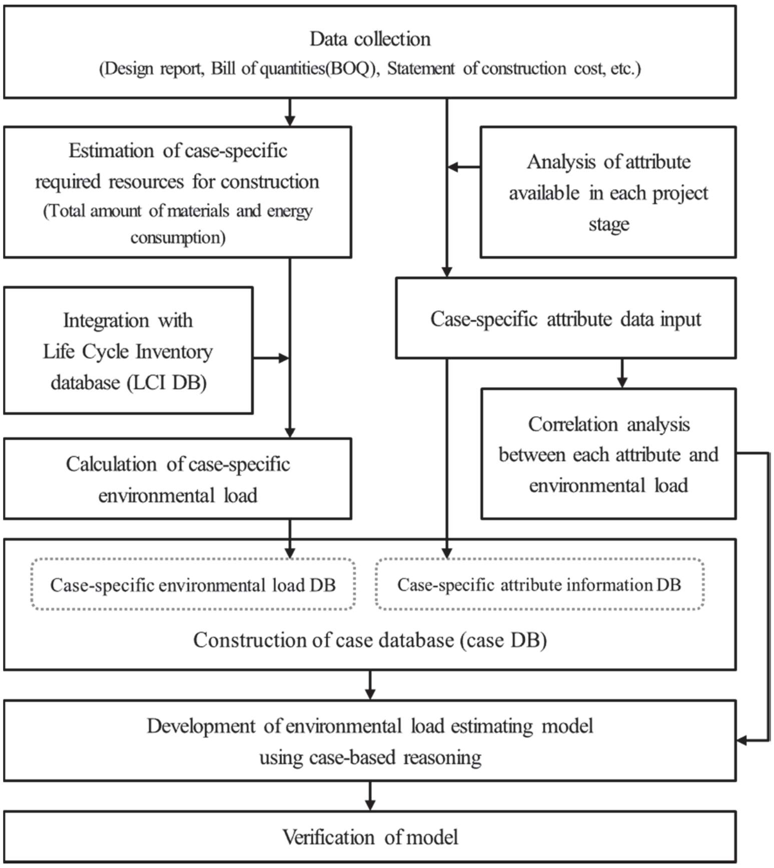

Fig. 1. Research flow chart

The case DB consists of the environmental load DB and the attribute information DB. The case-specific environmental load DB was obtained by calculating the quantities of the required resources from the design data, then integrating these quantities with the Life Cycle Inventory (LCI) DB to calculate the environmental load, and then creating the respective DB for each case. The case-specific attribute information DB was built by collecting the basic and design information of each project (e.g. tunnel name, project section, tunnel length, number of lanes etc.).

Among the attributes, those factors which had an influence on environmental load were used as input variables to find similar previous cases in the estimating model. To determine these influential factors, a correlation analysis was conducted between each attribute and environmental load.

Lastly, the case DB and influential factors were used to develop an environmental load estimating model for a new project case. To verify the proposed model, the estimating model of this study was validated by comparing the environmental load estimated based on the detail design data (actual value). In addition, the accuracy of the estimating model was verified by comparing with the environmental load estimated using the basic unit method.

Generally, the LCA for structure is divided into the construction stage, operation and maintenance stage, and demolition and disposal stage (Dumitrescu et al., 2014). In this study, the environmental load of the tunnel at the construction stage was considered because it is possible to identify the actual quantities of input materials and energy consumption from the design data (Fig. 2). However, the environmental load of the tunnel at the operation and maintenance stage was excluded from the scope of this study because it is usually calculated based on assumptions (e.g. operation plan, maintenance method and cycle, etc.). Also, as the demolition and disposal of tunnels is rarely performed in reality, since tunnels are usually retained, the environmental load at of the tunnel at the demolition and disposal stage was also excluded from the scope of this study.

2. Methodology

2.1. Life Cycle Assessment (LCA)

In the construction industry, the LCA is used as a decision-making tool to assess environmental impacts by quantifying environmental loads (including pollution, waste water, and flying dust) through the life cycle of a structure, including manufacturing and fabrication of construction materials, construction, operation and maintenance, and demolition and disposal. It is an active and systematic evaluation method used to reduce pollution through a proactive prevention effort rather than through the post-treatment method typically used in the construction industry. As an important tool for assessing the environmental impacts of construction, the LCA can thus contribute to realizing the ideology of ‘Environmentally Sound and Sustainable Development (ESSD)’ (MOCT, 2003).

To perform the life cycle assessment, all data associated with the product’s life cycle (raw materials acquisition and manufacturing, transportation, use, disposal, etc.) is required. In reality however, it is very difficult to collect all of this data. Therefore, a LCI DB that guarantees accuracy and reliability is used. In South Korea, 415 National LCI DBs have been developed by the Korea Environmental Industry Technology Institute (KEITI) and are currently used (KEITI, 2016).

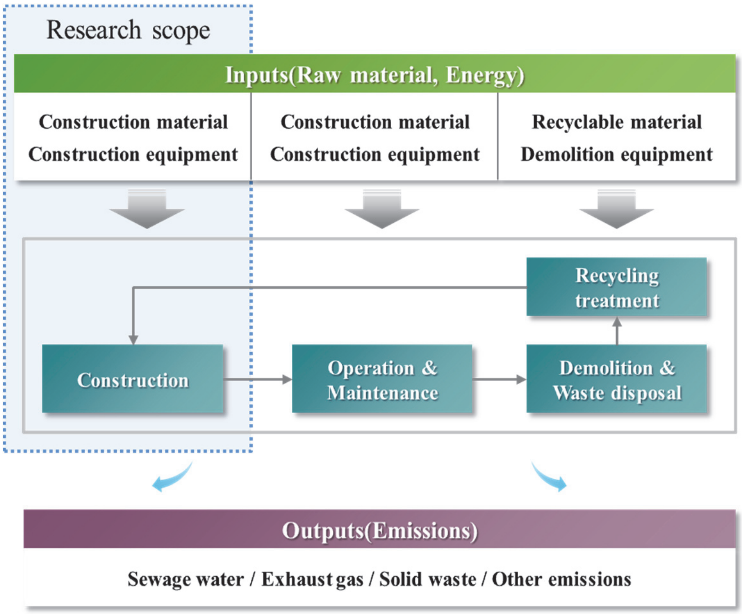

Fig. 2. Research scope

2.2. Case Based Reasoning (CBR)

First presented by Schank and Abelson (1977), the CBR is a problem solving paradigm that in many respects is fundamentally different from other major AI approaches (Aamodt and Plaza, 1994). The CBR process is similar to the decision making process of an individual, wherein one utilizes the existing cases when solving problems. When faced with new problems, one can present optimal solutions by exploring existing cases similar to the new one, and by comparing the cases in multiple ways. That is, new problems can be dealt by studying the solutions to prior experiences. CBR methodology estimates the project data of a test case (i.e., cost or duration) based on the characteristics in a similar case that were extracted from the database (Doğan et al., 2008). Compare to the parametric methodology which has typically been used as a predictive model in the planning and designing phases, CBR produces more precise results (Duverlie and Castelain, 1999).

In CBR, the *Case* plays a pivotal role, and *Case Base* is the accumulation of all similar cases. Besides, the values inherent in *Case Base* are not made theoretically, but are actual ones that occurred in the past, thus presenting improved solutions via the process of application, inference and modification of the existing cases under suitable conditions.

Fig. 3 shows the classic model of a problem solving cycle using the CBR methodology. CBR is composed of the four REs process of *retrieve*, *reuse*, *revise* and *retain*. In order to solve new problems, CBR retrieves one or more previously experienced cases, and reuses the case in one or more ways. Revise requires modifying the solutions of the previously cases based on its reuse, and retain means to store the solutions derived from modifying the previous resolution in existing data (Aamodt and Plaza, 1994).

3. Literature review

Over past two decades, ample studies have been conducted using LCA methodology to explore the environmental impact from activities of the construction industry (Huang et al., 2015). Various quantification studies centring on Europe and the US, were conducted on the cause of the environmental impacts occurring at each stage, including material production, construction, operation and maintenance. Hwang et al. (2000) assessed the CO_2 emissions caused by the combustion of fossil fuels during road construction by evaluating the impact and contribution of road construction to global warming. Junnila and Horvath (2003) quantified the significant environmental aspects of a new high-end office building over 50 years of service life including data quality assessment. Cass and Mukherjee (2011) proposed the method to quantify the life-cycle emissions associated with different pavement designs using a hybrid LCA. Choi and Kim (2013) divided a natural gas plant facility into subcategories- materials, pipeline installation, supply management office, and assessed their respect CO_2 emissions.

LCA methodology was further applied to a range of studies on presenting environment-friendly alternatives, by comparing and analyzing the environmental impact of diverse factors, such as type of structure, main materials, and construction method. Collings (2006) conducted a study to assess the energy use and the range and variability of CO_2 emission of concrete, steel, and steel-concrete composite materials used for bridges. Piratla et al. (2012) presented a methodology to quantify the CO_2 emissions from the life cycle of a potable water project. After comparing the CO_2 emissions from of four types of pipes (PVC-O, PVC-U, HDPE, and Ductile iron), it was found that PVC-O pipe was the most environment-friendly.

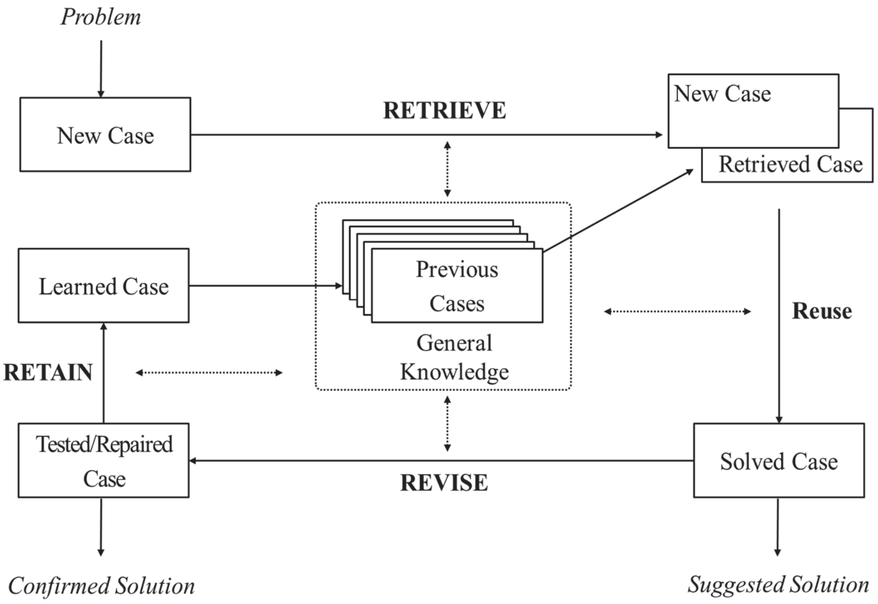

Fig. 3. CBR cycle (Aamodt and Plaza, 1994)

Similarly, Liu et al. (2013) evaluated the life-cycle environmental loads of a Conventional Concrete (CC) dam and the Rock-Filled Concrete (RFC) dam, and the results of the comparative analysis showed that the energy consumption amount of the CC dam was 55% less than that of the RFC dam, which is equivalent to a 64.5% decrease in the CO_2 emissions. Dumitrescu et al. (2014) evaluated the impact of asphalt and concrete pavement from two specific case studies. These studies have contributed much to design for environment in the construction industry by providing the information needed to select materials or construction methods with low environmental impacts.

Nevertheless the above-mentioned studies have some inherent limitations. The existing studies about LCA for Social Overhead Capital (SOC) facility require detailed design information about the used amounts of materials and equipment with the bill of quantities(BOQ) and the cost estimation document, it is not easy to evaluate the environmental load prior to design completion. For such reason, the method of estimating environmental load using basic unit (e.g. carbon emissions per the length of road) at the planning stage is applied, but it does not accurately reflect the features of individual project.

In order to overcome such limitations, several studies have attempted to develop an environmental load estimating model by inputting the basic data of facilities. Jeong et al. (2015) developed the environmental load estimating model for educational facilities, by including number of stories, the building area and structure type set as input variables, and used the Input-Output LCA (I-O LCA) method for calculating environmental load. Moon et al. (2014) developed a model for residential buildings in South Korea, with structure type, household type and foundation type set as input variables, and employed the Hybrid LCA combining Process LCA and I-O LCA. I-O LCA calculates the quantity of direct and indirect energy source consumed in producing materials via input coefficient and production inducement coefficient of inter-industry table, using the expense invested in the materials. Though less time is spent on analysis and calculation in comparison with Process LCA, the disadvantage of I-O LCA is that the causative factor of the environmental load is limited to the energy source, resulting in a less accurate estimation (Bliec, 2007) because the quantity of calculated energy source is only an estimated value using the inter-industry table. In contrast, Process LCA, a method to conduct inventory analysis by estimating a series of process charts for the types and quantity of all materials introduced to manufacture a product, and also including the emissions and by-products released according to the materials used, is more accurate than I-O LCA, and a comparison between individual products is possible.

For these reasons, most of the software in practical use in foreign countries conforms to process LCA, and the national LCI DB of South Korea also was established using the process LCA.

This study therefore aims to build a case base for the environmental load of each case by using the Process LCA that is more precise. Besides, this study utilized a CBR methodology which can be used for predicting the environmental loads of new case by using the similar case from the case base. It is expected that the proposed model using CBR will be able to estimate the environmental loads at the planning stage that design information available is limited. And it will also be more accurate than the basic unit method that is not reflected the features of individual project. To verify this, this study was conducted the comparison of estimation results between the basic unit method and the proposed model.

4. Construction of case DB

4.1. Data collection

First of all, in order to build an environmental load estimating model using CBR, design data were collected (including design report, bill of quantities, statement of construction cost, unit price list, etc.) for a total of 81 NATM tunnels, which were selected among the national highway construction projects in South Korea. The collected data on the current status of the tunnels are shown in Table 1.

Table 1. Current status of data collected

Division		***Cases***
Number of lanes	2	69
	3	8
	4	4
Type of traffic	Unidirectional traffic	61
	Bidirectional traffic	20
Type of ventilation	Natural ventilation	56
	Mechanical ventilation	25
Tunnel length	More than 3,000m	6
	More than 1.000m and less than 3.000m	40
	More than 500m and less than 1.000m	22
	Less than 500m	13

4.2. Analysis of attribute information available in design stage and construction of attribute information DB

At the planning stage, the optimal road route is selected after conducting a comparative analysis on several candidate road routes. In some cases, it is possible to know the location of a tunnel, and its start and end points, as well as the approximate extension. Also, various options about the lane number and passage methods, such as a large-section bidirectional traffic tunnel with four lanes or a unidirectional traffic tunnel with two lanes, are reviewed considering tunnel length, construction costs, and ground conditions. The design speed is planned after considering road classification according to the total number of lanes and connectivity with adjacent roads.

In the basic design stage, the optimal road route selected in the planning stage is compared with 2 or 3 comparable routes, and more detailed information can be used. The optimal cross section of the road structure and design criteria will be chosen considering the disaster prevention grade and ventilation method, and the type of tunnel portal will be determined considering the adjacent geographic conditions according to the location of the tunnel and its start and end points on the comparable routes. In the detailed design stage, the optimal road route will be finally selected and, based on the detailed route, the detailed road alignment design and detail design will be executed.

The generally available attribute information levels according to respective design stages are shown in Fig. 4. As previously stated, an estimating model will be developed based on the previous cases by using the information available in the planning and basic design phases prior to the detail design stage. Therefore, an attribute information DB was developed in this study by collecting the information available before the detail design stage.

The attribute data items and types required to create the case-specific attribute information DB are shown in Table 2. After examining the relevant attribute information collected from the design data of the respective case, the data were entered into the DB. The basic information such as tunnel name, section, completion year, and project owner was also included in the DB for providing the general information of the tunnel project.

4.3 Construction of environmental load DB

In order to build an environmental load DB, the construction cost estimation program was used to calculate the total quantities of materials and equipment used in the respective NATM tunnel project, based on the BOQ and the statement of construction cost. Table 3 shows part of the total required resources for construction in one example from the collected design data.

These resources need to be integrated with the LCI DB to estimate the environmental load. Twenty-four LCI DBs were utilized in this study, 20 of which were national LCI DBs that had been established by the Ministry of Knowledge and Economy (MKE) and the Ministry of Environment (ME) in South Korea, and 4 of which were domestic LCI DBs established in 2005 by the Korea Institute of Civil engineering and building Technology (KICT). For the materials including asphalt, PVC, sodium silicate, propane gas, acetylene, and asphalt concrete, the Eco-invent DB (an overseas LCI DB) was used. For rockbolts, the DB was developed by the research team employed in this study. The LCI DBs used in the study are listed in Table 4.

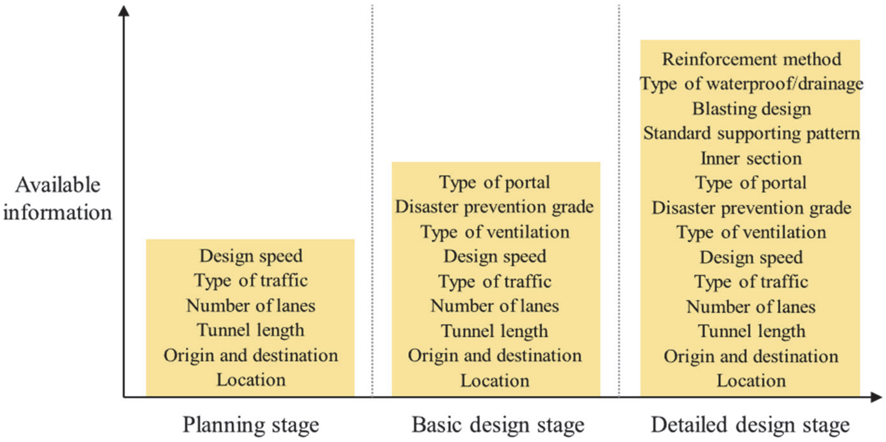

Fig. 4. Classification of available information by design stage of NATM tunnel

Table 2. Attribute data of NATM tunnel

Attribute	*Type*	*Note*
Tunnel name	Text	Basic information
Project section	Text	Basic information
Completion year	Number	Basic information
Owner	Text	Basic information
Location	Text	Administrative district
Length	Number	
Number of lanes	Number	2/3/4
Type of traffic	Text	Unidirectional traffic/Bidirectional traffic
Design speed	Number	
Type of ventilation	Text	Natural ventilation/Mechanical ventilation
Disaster prevention grade	Number	1/2/3/4
Type of tunnel portal	Text	

Table 3. Required resources for construction using a construction cost estimation program (part of the total resources)

Resource	***Standards***	***Quantity***	***Unit***	***Unit Cost (KRW)***	***Amount (KRW)***
Light fuel oil		371,364.93	L	1,027	381,391,783
Remicon	25-240-15	7,136	m^3	51,936	370,615,296
Rockbolt	D25 5.0m	4,980	ea	20,000	99,601,000
Deform bar	D19M/M 2.250kg/m	146.551	ton	493,000	72,249,643
Normal Portland cement	40kg/sack	17,276	sack	2,820	48,718,320
Silicate of soda		193,800	kg	170	32,946,000

Table 4. LCI DBs used in this study

DB	***Materials***	***Unit***
National DB (MKE, ME)	Portland Cement	kg
	Remicon 25-240-15	m^3
	Expanded Polystyrene (EPS)	kg
	Oxygen (O_2)	ton
	Wire rod	ton
	Stainless steel	kg
	Aluminum strip	kg
	Epoxy adhesive	kg
	Acrylic emulsion adhesive	kg
	Hot rolled steel coil	ton
	Low-density polyethylene (LDPE)	kg
	Electric steel deformed bars	kg
	Electric steel sections	kg
	Carbon steel	kg
	Brass bar	kg
	Steel plates	ton
	Light fuel oil	kg
	Electricity	kWh
	Gasoline	kg
	PET film (Polyethylene terephthalate film)	kg
Domestic DB (KICT)	Sand	m^3
	Plywood	m^3
	Tile	kg
	Gravel	m^3
Domestic DB (SOC-LCA Research Team)	Rockbolt D25 2.5m ~ 8.0m	set
Overseas DB (Eco-invent DB)	Asphalt	kg
	Polyvinylchloride (PVC)	kg
	Sodium silicate	kg
	Liquefied petroleum gas	kg
	Acetylene	kg
	Asphalt concrete	ton

In order to estimate the environmental load associated with the quantities of required resources and energy consumption, the study integrated them with the LCI DB. If the quantity unit used in the statement of construction cost differ to that used in the LCI DB, it should be converted to correspond to the quantity unit of the LCI DB. For example (Eq. 1), in the case of light fuel oil, 'liter' (ℓ) was used in the statement of construction cost, whereas 'kilogram' (kg) was used in the LCI DB. Therefore, liters were converted into kilograms according to the density of light fuel oil of 0.83kg/ ℓ.

Volume of light fuel oil (ℓ) × Specific weight of light fuel oil = Weight of light fuel oil (kg)→ 1 ℓ × 0.83kg/ ℓ = 0.83kg (1)

The other materials and fuels were also converted into the units used in the LCI DB. These converted total quantities were integrated with the LCI DBs to estimate the total environmental load of tunnels.

Data collected on resources (materials and fuels or energy consumed by equipment) were integrated with the LCI DB to calculate the environmental load of 81 NATM tunnels and to create a DB for these tunnels. The categories of environmental load included the 8 major impact categories proposed by the 'Korea Indicator (MCIE, 2003)', the impact assessment methodology developed by the Ministry of Industry, Commerce and Trade to apply to the Korean context (Table 5): Abiotic Resources Depletion (ARD), Acidification (AC), Eutrophication (EU), Global Warming (GW), Ozone Depletion (OD), Photochemical Oxidant Creation (POC), Eco-Toxicity (ET), and Human Toxicity (HT). To compare the environmental load quantities calculated with different units, normalization and weighting processes were followed. After undergoing the normalization and weighting processes, the environmental load quantities were finally converted into Eco-points. Summing the total Eco-points enabled comparison of the environmental load between different projects.

Table 6 shows the quantities of materials and their subsequent environmental load scores of a project among the 81 project cases. By using this method, the study created the DB of the environmental load of 81 projects to estimate the environmental load of a new project.

5. Development of environmental load estimating model for NATM tunnel using case based reasoning

For estimating the environmental load of a new project to propose alternative options, data on previous projects similar to the new project were extracted from the above established case-specific environmental load DB. The environmental load estimating model was then developed to estimate the possible environmental loads of the new project based on previous similar projects. The processes of the estimating model are shown in Fig. 5.

Table 5. Environmental impact categories of the Korea indicator

Impact Category	***ARD***	***AC***	***EU***	***GW***	***OD***	***POC***	***ET***	***HT***
Unit	1/yr	kg SO_2-eq	kg PO_4^{3-}-eq	kg CO_2-eq	kg CFC11-eq	kg C_2H_4-eq	kg 1,4 DCB eq	kg 1,4 DCB eq
Normalization Factor	24.9	39.8	13.1	5530	0.0407	10.3	1.63	1480
Weight Factor	0.231	0.036	0.038	0.288	0.292	0.065	0.216	0.105
Converted Unit	Eco-point	Eco-point	Eco-point	Eco-point	Eco-point	Eco-point	Eco-point	Eco-point

Table 6. Material quantities and environmental loads of case 1

Material	***Unit***	***Quantity***	***Environmental load (Unit: eco-point)***								
			ARD	***AC***	***EU***	***GW***	***OD***	***POC***	***ET***	***HT***	***Sum***
Remicon	m^3	52,817.28	715.67	33.70	12.55	1180.47	14.49	319.39	10.97	202.87	2490.11
Cement	kg	6,373,124.68	61.41	3.26	0.01	314.77	0.65	97.89	0.84	9.60	488.44
Diesel	kg	1,395,311.79	340.74	0.18	0.04	4.96	0.00	0.10	0.00	0.02	346.03
Wire rod	ton	485.07	58.89	7.93	1.68	240.26	0.25	1.12	0.70	6.46	317.27
Sodium silicate	kg	318,821.05	0.00	1.50	2.73	26.59	0.23	0.84	117.10	27.50	176.49
Rockbolt D25 4.0m	set	14,732.09	27.51	0.03	0.02	28.59	0.04	0.30	0.77	1.10	58.34
Deformed bars	kg	979,688.93	16.85	0.39	0.00	22.34	0.06	1.96	0.39	1.19	43.18
Carbon steel	kg	155,094.13	17.36	0.27	0.01	18.91	0.02	0.64	1.90	0.78	39.88
Stainless steel	kg	16,711.21	3.60	0.07	0.01	2.81	0.15	0.01	4.09	5.54	16.29
Tile	kg	242,227.44	4.04	0.04	0.00	4.45	0.02	0.02	0.05	0.15	8.77
Rockbolt D25 3.0m	set	2,928.29	4.10	0.00	0.00	4.26	0.01	0.04	0.11	0.16	8.70
Steel sections	kg	133,880.17	2.82	0.16	0.07	2.99	0.02	0.26	0.05	0.35	6.72
Plywood	m^3	53.16	1.15	0.20	1.09	2.27	0.02	0.06	0.80	0.38	5.97
Gravel	m^3	5,416.82	2.00	0.00	0.00	3.20	0.00	0.00	0.00	0.04	5.25
Sand	m^3	9,461.44	1.36	0.09	0.05	1.91	0.01	0.01	0.01	0.40	3.84
Hot rolled steel coil	ton	5.56	0.65	0.01	0.00	0.51	0.00	0.16	0.00	0.00	1.33
EPS	kg	1,691.57	0.32	0.01	0.00	0.17	0.00	0.07	0.00	0.20	0.78
PVC	kg	2,802.89	0.00	0.01	0.01	0.29	0.00	0.04	0.03	0.05	0.44
Rockbolt D25 5.0m	set	80.34	0.19	0.00	0.00	0.19	0.00	0.00	0.01	0.01	0.40
Steel plates	ton	1.72	0.14	0.00	0.00	0.08	0.00	0.03	0.00	0.01	0.26
Gasoline	kg	532.92	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13
Acetylene	kg	44.54	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.05
Oxygen	ton	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sum			1258.92	47.86	18.27	1860.01	15.98	422.94	137.85	256.83	4018.65

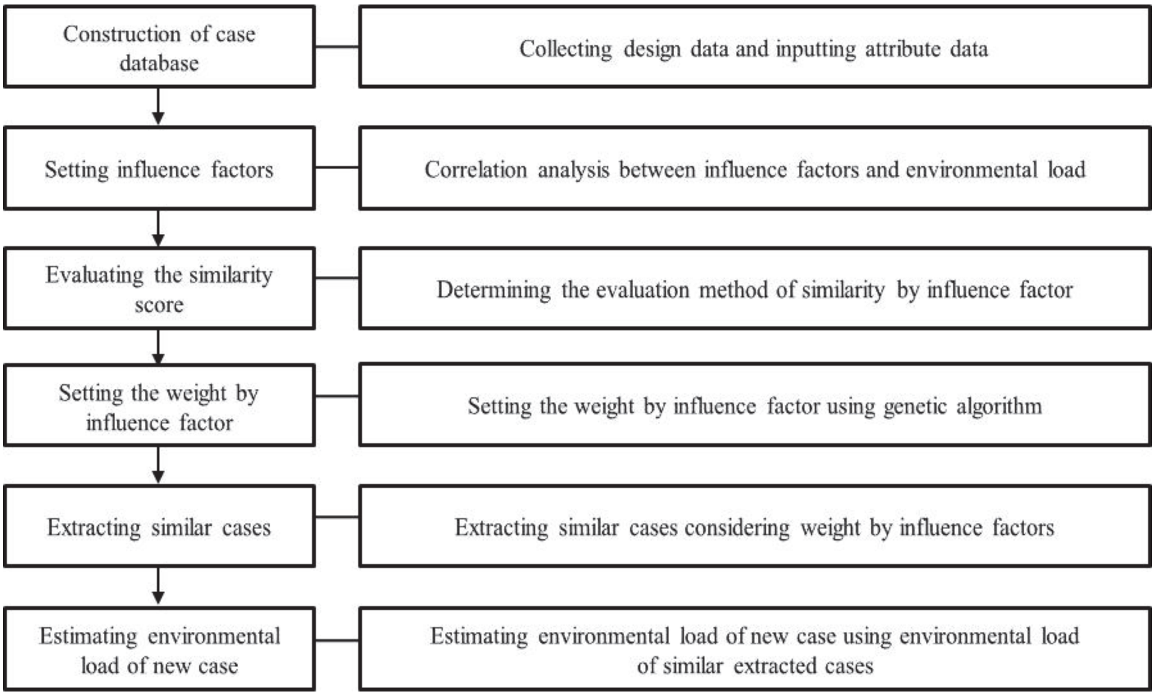

Fig. 5. Estimating process of environmental load of new case

5.1. Setting of influence factors of environmental load

Correlation analysis was performed to identify the factors that influence the environmental load among the attribute information of the previous projects. The selected influence factors were utilized to evaluate the similarity between projects in order to extract similar cases from the DB of the previous projects. For example, as the correlation between tunnel length and environmental load is high, as shown in Fig. 6, the attribute information 'length' becomes an influence factor, which is utilized to extract the previous projects with attribute information length similar to the new project.

In order to estimate the environmental load only with the data available in the planning stage, correlation analysis was performed on a candidate group of influence factors, while excluding those data that will be specified in the detailed design stage (Table 7).

Table 7. Correlation analysis on a candidate group of influence factors

Variable type	*Candidate group of influence factors*
Continuous variable	Tunnel length
	Design speed
Categorical variable	Number of lanes
	Type of traffic
	Type of ventilation
	Disaster prevention grade
	Type of tunnel portal
	Administrative district

An analysis was performed of the correlation between environmental load and continuous variables such as tunnel length and design speed through the Pearson correlation coefficient. Analysis showed that the correlation coefficient value between tunnel length and environmental load was remarkably significant and positive at 0.950. Likewise, the correlation coefficient value between design speed and environmental load was statistically meaningful and positive at 0.377 (Table 8).

In order to analyze the correlation between environmental load and categorical variables with two independent variables (such as type of traffic (unidirectional traffic/bidirectional traffic) and type of ventilation (natural ventilation/mechanical ventilation)), an independent sample *t* test was performed.

The one-way analysis of variance (ANOVA) method was used to analyze the correlation between environmental load and categorical variables with more than three independent variables, such as number of lanes (2/3/4), disaster prevention grade (1/2/3/4), administrative district (Gyeonggi/Gangwon/Gyeongnam/etc.), and type of tunnel portal (Cylinder cut shape/Bell mouth/etc.). To overcome the increasing effect of environmental load by tunnel length, the environmental load per length (eco-point/m) was used as the dependent variable.

After conducting the independent sample *t* test, the difference between unidirectional traffic and bidirectional traffic was statistically significant at the 0.05 a-level. However, the difference between natural ventilation and mechanical ventilation was not significant at the 0.05 a-level (Table 9).

After conducting the one-way ANOVA, the difference among the group of number of lanes, disaster prevention grade, and administrative district was significant at the 0.05 a-level. However, the difference according to the type of tunnel portal was not significant at the 0.05 a-level (Table 10).

Table 8. Correlation between environmental load and tunnel length/design speed

		Tunnel length	***Design speed***	***Environmental load***
Tunnel length	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	81		
Design speed	Pearson Correlation	.377**	1	
	Sig. (2-tailed)	.000		
	N	81	81	
Environmental load	Pearson Correlation	.950**	.440**	1
	Sig. (2-tailed)	.000	.000	
	N	81	81	81

***p<.01*

Table 9. Independent sample *t* test result

		Type of traffic	***Type of ventilation***
Levene's test for equality of variances	Sig.	.000	.032
Independent sample t test	*t*	-2.764	.616
	Sig.	.011	.540

Table 10. One-way ANOVA Result

		Number of lanes	***Disaster prevention grade***	***Administrative district***	***Type of tunnel portal***
Equality of variances	Sig.	.996	.000	.001	.170
ANOVA	Sig.	.000	.000	.014	.118

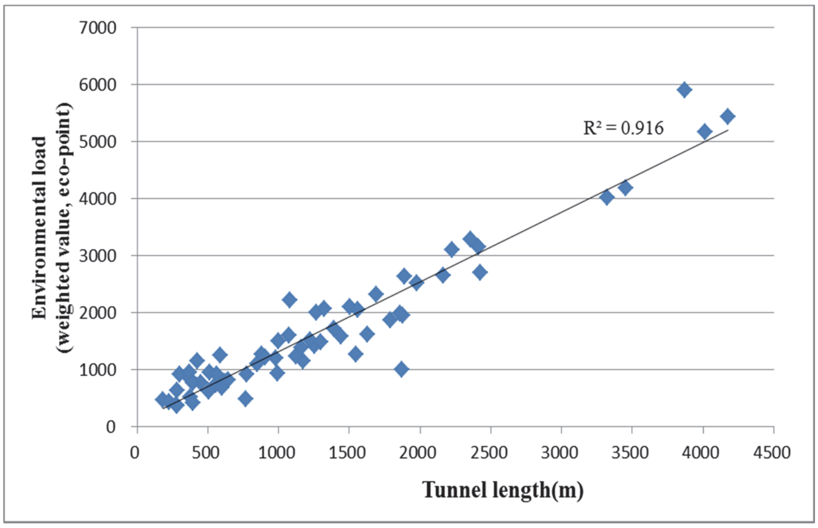

Fig. 6. Correlation between tunnel length and environmental load

Finally, five influence factors were selected from the correlation analysis, as shown in Table 11. Disaster prevention grade is closely related with the tunnel length because each tunnel is classified into four grades of 1 to 4 according to tunnel length in South Korea. Therefore, disaster prevention grade was excluded from the influence factors because of redundancy.

5.2. Calculation of similarity scores and extraction of similar cases

In the calculation of similarity scores for extraction of similar cases, the string similarity scoring method was applied to attribute information such as number of lanes, type of traffic, design speed, and administrative district, whereas the numerical similarity scoring method was applied to the tunnel length (Table 12).

When the string similarity was matched, a score of 100 was given, and when it was unmatched, a score of 0 was given. When the attributes were within the ranges of numerical similarity, a score of 100 was given, and when they were outside the range, a score of 0 was given. The similarity score calculation is seen in Eq. (2).

$$S_i = \sum_{1}^{j} (I_{ij} \times w_j) \qquad (2)$$

where i = case identification number; j = attribute identification number; S_i = similarity value of case I; I_{ij} = similarity value of attribute; and w_j = weight of attribute j.

Table 11. Influence factors of environmental load estimating model of NATM tunnel

Influence factors of environmental load estimating model using CBR				
Tunnel length	Number of lanes	Type of traffic	Design speed	Administrative district

Table 12. Similarity score calculation method by attribute value

Attribute value	***Calculation method of similarity score***
String similarity	Score is awarded when the case's attribute value is exactly the same as the existing case's attribute
Numerical similarity	Score is awarded when the case's attribute value is within the range of numerical similarity $\left\| \frac{V_{existing\ \ case} - V_{new\ case}}{V_{new\ case}} \right\| \times 100 \le Similarity\ \ \ range$

In terms of the numerical similarity scoring method, the similarity scores might vary depending on the different similarity setting values. Therefore, in order to determine the optimal similarity range, the similarity range was divided into groups of 10%, 20%, and 30% and the similarity range that could minimize the absolute error rate of the learning case was identified.

Also, based on the assigned scores, the ranking of each case was determined; however, a decision needed to be made on the number of top rankers that will be selected as similar cases. If only the top ranking case is to be selected, the estimation of the environmental load of the new project will depend on the very limited number of previous cases. In contrast, if the top five cases are selected, several cases that have relatively low similarity might be included. Therefore, after assessing and comparing the similarities among the top case and the top five cases, the number of top ranking cases that will be used to produce the optimal results was determined.

The correction process of similarity scores and tunnel length for the selected similar cases was carried out to estimate the environmental load. Weighting values were then given according to the percentage of the similarity score of the concerned case compared to the total scores of all similar cases. Therefore, more cases with higher similarity scores were reflected in the estimation of environmental load.

The correction process of tunnel length was performed because it was necessary to correct the linear change in environmental load value according to the characteristics of tunnel length, as seen in Fig. 6. The estimated environmental load values after the correction of similarity scores and tunnel length can be estimated using (Eq. 3).

$$W_i = \frac{S_i}{\sum_{1}^{n} S_i} \qquad E = \sum_{i}^{n} (W_i \times L_i \times O_i) \tag{3}$$

where W_i = similarity weight of the retrieved similar case i; n = number of retrieved similar cases; E = estimated environmental load of the new case; L_i = ratio of tunnel length to new case with case i (tunnel length of the new case/tunnel length of case i); and O_i = environmental load of case i.

5.3. Weighting values of influence factors

A non-linear correlation was observed between the objective function used to minimize the absolute error rate in the estimated environmental load based on the previous cases and the weighting values of the influence factors. Therefore, a genetic algorithm was applied to the calculation of the weighting values of influence factors. The genetic algorithm was used to deduce the environmental load of multiple learning cases, and the weighting value that could minimize the mean absolute error rates (MAER) of the presumed environmental load was then calculated. Seven learning cases were utilized in this study.

The attribute weighting values can vary depending on the similarity ranges (%) and ranking standards used for the assignment of scores to numeric and string similarity in the selection of similar cases. Therefore, the MAERs were analysed by dividing the similarity range into groups of 10%, 20%, and 30% and by classifying the ranking standards into groups ranging from the top to the top 5 in order to identify the optimal weighting values.

The results are shown in Table 13. According to the analysis results, when the similarity range was within 10% and the top 3 in the similarity rankings were selected, the MAER of the learning cases was estimated to be 6.3%. Therefore, the weighting values that were calculated by selecting the top 3 cases with a similarity range of within 10% were applied to the estimating model (Table 14).

6. Verification of model

6.1. Comparison of estimating results

To verify the absolute error rates of the estimating model, the estimated values of 10 cases were compared with the actual values. The attribute information used for the verification of the estimating model are shown in Table 15.

Table 13. Weighting values of influence factors (Attributes) and MAER result according to the range of similarity and rank

Range of similarity	*Rank*	*Weighting Values of Influence Factors (attributes)*					*MAER*
		Number of lanes	*Type of traffic*	*Tunnel length*	*Design speed*	*Administrative district*	
10	1	0.2678	0.2878	0.1213	0.0203	0.3027	11.1%
	2	0.0407	0.0922	0.3673	0.1506	0.3491	7.6%
	3	**0.2616**	**0.0732**	**0.2956**	**0.1050**	**0.2646**	**6.3%**
	4	0.4714	0.0635	0.2248	0.1366	0.1037	7.2%
	5	0.4892	0.1390	0.2030	0.0572	0.1116	7.9%
20	1	0.2798	0.0573	0.3125	0.0000	0.3504	10.5%
	2	0.0945	0.1088	0.3781	0.0408	0.3779	8.3%
	3	0.3465	0.2545	0.0946	0.0188	0.2856	9.1%
	4	0.4337	0.0385	0.2423	0.0000	0.2854	9.6%
	5	0.4202	0.1263	0.1530	0.0000	0.3006	9.1%
30	1	0.2954	0.2472	0.0000	0.1810	0.2763	11.1%
	2	0.1340	0.1155	0.3821	0.0531	0.3154	8.0%
	3	0.3946	0.0729	0.2688	0.0289	0.2348	8.9%
	4	0.4555	0.0302	0.2099	0.0000	0.3043	10.1%
	5	0.4751	0.0000	0.1502	0.0952	0.2795	9.8%

Table 14. Weighting values of influence factors

Attribute	*Number of lanes*	*Type of traffic*	*Tunnel length*	*Design speed*	*Administrative district*
Weight	0.2616	0.0732	0.2956	0.1050	0.2646

The actual values were the environmental loads that were calculated based on the previous detail design data, whereas the estimated values were the environmental loads that were estimated by applying input variables (including number of lanes, type of traffic, length, design speed, and administrative district) to the estimating model, which was developed based on the CBR methodology. Table 16 shows the comparison results of the 8 major environmental impact categories, the absolute error rates (AER) of each case, and the MAER of 10 cases.

According to the verification results of the 10 cases, the MAER was 8.9%, the maximum error rate was 18.6%, and the minimum error rate was 1.7%. This result means that the estimated result of the environmental loads based on the CBR approach is significant at the planning stage. In case of cost estimation, the expected accuracy range is from -35% to +35% at the planning stage and from -20% to +20% at the preliminary design stage (MOTI, 2013). Therefore the results from the verification cases can also show that it is possible to estimate the environmental loads of tunnel construction at the planning stage.

6.2. Comparison with results using basic unit method

To evaluate the relative accuracy of the estimating model, a comparative analysis conducted with the estimation method of environmental load using the basic unit method. First, the basic unit of environmental load (Eco-point/length×number of lanes) was calculated by utilizing the case-specific environmental load DB, the results of which are shown in Table 17. The basic unit was calculated by dividing the total environmental load with the approximate area size of the length multiplied by the number of lanes. By using the basic unit, the environmental loads of the ten cases that were used for the verification of CBR model were calculated. The calculated environmental loads were then compared with the actual environmental load and then with the estimated values of the estimating model. The results are shown in Table 18 and Fig. 7.

According to the estimation results of the environmental load of the 10 verified cases using the basic unit method, the MAER was 21.4%, the standard deviation (SD) was 12.9%. In the case of the estimation of environmental load using the basic unit method, 7 cases exceeded the error rate of 20% among the 10 verification cases. In contrast, the CBR model showed an error rate of from –20% to +20%, the MAER was 8.9%, and the SD was 6.0%. These results mean that the estimating model developed in this study is more accurate and more reliable than the estimation method of the basic unit method.

7. Conclusions

This study developed a model that could estimate the environmental loads of NATM tunnels in the planning stage. In order to build an environmental load estimating model using the case based reasoning, this study collected design data of 81 NATM tunnels including design report, bill of quantities, statement of construction cost, unit price list, etc. Information for tunnel attributes available in the planning and basic design phases prior to the detail design stage were identified and collected to be utilized as input variables of the model.

Table 15. Attributes of verification case

Case	***Number of lanes***	***Type of traffic***	***Tunnel Length(m)***	***Design Speed(km)***	***Administrative district(province)***
1	2	Unidirectional traffic	1790	80	Gyeongbuk
2	2	Unidirectional traffic	1856	80	Jeonbuk
3	2	Unidirectional traffic	3326	80	Jeonnam
4	2	Bidirectional traffic	878	60	Gyeongbuk
5	2	Bidirectional traffic	393	60	Jeonnam
6	3	Unidirectional traffic	1890	100	Chungnam
7	3	Unidirectional traffic	3870	100	Gyeonggi
8	3	Bidirectional traffic	1080	100	Gyeonggi
9	4	Bidirectional traffic	370	70	Jeonbuk
10	4	Bidirectional traffic	425	80	Jeonbuk

Table 16. Estimating results according to verification cases (unit: eco-point)

		ARD	***AC***	***EU***	***GW***	***OD***	***POC***	***ET***	***HT***	***TOTAL***	***AER (%)***	***MAER (%)***
Case 1	Actual	661.4	20.5	9.1	811.5	5.9	176.4	141.1	113.3	1939.2	5.1%	8.9%
	Estimated	654.9	22.9	8.8	956.5	6	202.9	82.6	103.9	2038.6		
Case 2	Actual	589.3	23.9	9.9	955	6.6	203.6	79.6	110.9	1978.6	10.6%	
	Estimated	699.9	24.9	9.7	1019.7	6.2	215.7	101.1	110.6	2187.9		
Case 3	Actual	1258.9	47.9	18.3	1860	16	422.9	137.8	256.8	4018.6	1.7%	
	Estimated	1219	44.5	18.3	1824.8	13.3	407.6	193.8	230.3	3951.4		
Case 4	Actual	281.6	11.7	4.2	479	3.4	103	21.4	52.8	957.1	15.9%	
	Estimated	363.6	12.7	4.9	516.6	3.6	108.6	39.5	59.9	1109.3		
Case 5	Actual	127.7	4.9	2	195.1	1.5	43.2	14.1	23.9	412.3	14.5%	
	Estimated	141.3	5.6	2.4	223.7	1.7	48.8	20.6	28.2	472.2		
Case 6	Actual	890.4	26.7	11.5	1107.2	8.6	266	150.9	152.9	2614.1	4.2%	
	Estimated	929.8	29	12.2	1195.6	8.8	271.1	127.2	151.1	2724.7		
Case 7	Actual	1882.6	49.2	17.5	2767.6	12.3	667.2	247.6	243.1	5887	18.6%	
	Estimated	1661.3	55.7	22.7	2127.1	17.8	472.4	152.3	284.1	4793.4		
Case 8	Actual	565.3	16.5	6	827.3	3.8	184.9	70.7	70	1744.4	10.5%	
	Estimated	641.9	19.5	7.6	891.9	5.3	187.4	79.5	94.8	1927.9		
Case 9	Actual	318.4	11	4.4	416.1	2.8	85.1	58.5	52.4	948.5	2.4%	
	Estimated	292.9	10.2	4.5	413.6	2.7	84	65.4	52.6	925.9		
Case 10	Actual	392.5	12.4	4.7	516.9	3.2	105.2	59.7	59.2	1153.9	5.7%	
	Estimated	345.2	11.9	5.4	476.8	3.2	95.9	86.3	63.4	1088.1		

Table 17. Basic unit of environmental load of NATM tunnel

Environmental load per unit area (Eco-point /m·lane)	***Environmental load (weighted value, Eco-point/m·lane)***								
	ARD	***AC***	***EU***	***GW***	***OD***	***POC***	***ET***	***HT***	***Sum***
	0.2116	0.0075	0.0031	0.3022	0.0021	0.0638	0.0388	0.0376	0.6667

Table 18. Comparison between basic unit method and CBR model

Case	***Actual environmental load***	***Basic unit method***		***CBR Model (Case based reasoning)***	
		Estimated value	***Error rate***	***Estimated value***	***Error rate***
	eco-point	***eco-point***	***%***	***eco-point***	***%***
1	1939.2	2386.8	23.1%	2038.6	5.1%
2	1978.6	2474.8	25.1%	2187.9	10.6%
3	4018.6	4434.9	10.4%	3951.4	-1.7%
4	957.1	1170.7	22.3%	1109.3	15.9%
5	412.3	524.0	27.1%	472.2	14.5%
6	2614.1	3780.2	44.6%	2724.7	4.2%
7	5887.0	7740.4	31.5%	4793.4	-18.6%
8	1744.4	2160.1	23.8%	1927.9	10.5%
9	948.5	986.7	4.0%	925.9	-2.4%
10	1153.9	1133.4	-1.8%	1088.1	-5.7%
Mean Absolute Error Rate (MAER)		21.4%		8.9%	
Standard Deviation (SD) of Absolute Error Rate		12.9%		6.0%	

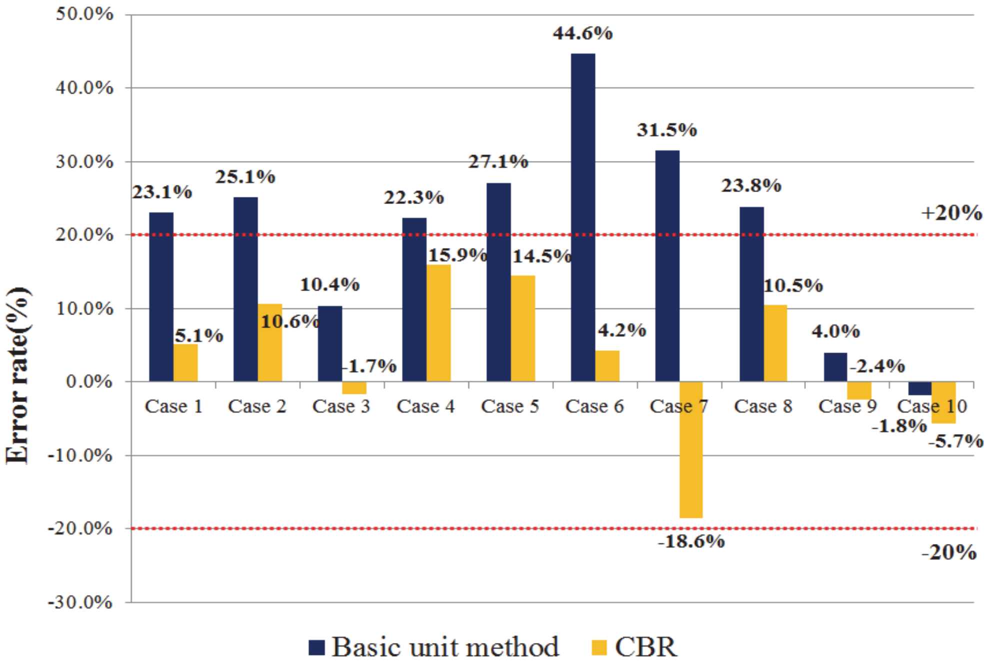

Fig. 7. Comparison between Basic Unit Method and CBR Model

In order to build an environmental load DB for tunnel, the construction cost estimation program was applied to calculate the total quantities of materials and equipment utilized in the respective NATM tunnel project, based on the BOQ and the statement of construction cost. Environmental load DB for tunnel projects was established by integrating these resources with LCI DB. In estimating the environmental load of a new project, data on previous projects similar to the new project were extracted from the above established case-specific environmental load DB.

In these processes, key impact factors in estimating the environmental load of NATM Tunnel were identified. Weights of the key impact factors were also calculated to extract similar previous cases from the DB based on genetic algorithm. This study developed an estimating model which can assess environmental loads for tunnel construction based on information available at the planning stage utilizing a case based reasoning approach. To validate the developed model, 10 verification cases were evaluated. The result showed that the MAER and SD of the proposed model were 8.9% and 6.0%, respectively, while the basic unit method were 21.4% and 12.9%, respectively. These results demonstrate that the proposed model is more accurate and more reliable than the basic unit method. In addition, the proposed model allows a project planner or an engineer to rapidly and accurately estimate the environmental loads because it utilizes information available at the early stage of a tunnel construction project such as tunnel length, number of lanes, type of traffic, design speed, administrative district.

The proposed model is expected to be a useful tool in reviewing environmental impacts of design alternatives and ensuring an environment-friendly design at the early stage of a project. Each case in the case DB of the proposed model has information about the quantities of construction materials and energy consumption from the use of equipment because it was constructed by using the process LCA method. Thus it would be useful data in analyzing environmental loads of each tunnel case in detail.

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References

Aamodt A., Plaza E., (1994), Case-based reasoning: Foundational issues, methodological variations, and system approaches, *AI Communications*, **7**, 39-59.

Bliec M., (2007), *A hybrid life cycle assessment model for construction process*, PhD Thesis, University of Pittsburgh, USA.

Cass D., Mukherjee A., (2011), Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: case study for pavement operations, *Journal of Construction Engineering and Management*, **37**, 1015-1025.

Choi D.Y., Kim S.K., (2013), A study on a carbon emission and reduction plan for the construction phase of a natural gas plant, *Journal of Korean Society of Hazard Mitigation*, **13**, 323-331.

Comanita E.-D. Cozma P., Simion I.M., Rosca M., Gavrilescu M., (2018) Evaluation of eco-efficiency by multicriteria decision analysis. Case study of eco-innovated and eco-designed products from recyclable waste, *Environmental Engineering and Management Journal,* **17**, 1791-1804.

Collings D., (2006), An environmental comparison of bridge forms, *Proceedings of the Institution of Civil Engineers - Bridge Engineering*, **159**, 163-168.

Doğan S.Z., Arditi D., Murat Günaydin H., (2008), Using decision trees for determining attribute weights in a case-based model of early cost prediction, *Journal of Construction Engineering and Management*, **134**, 146-152.

Dumitrescu L., Maxineasa S.G., Simion I.M., Taranu N., Andrei R., Gavrilescu M., (2014), Evaluation of the environmental impact of road pavements from a life cycle perspective, *Environmental Engineering and Management Journal*, **13**, 449-455.

Duverlie P., Castelain J.M., (1999), Cost estimation during design step: parametric method versus case based reasoning method, *The International Journal of Advanced Manufacturing Technology*, **15**, 895-906.

Huang L., Bohne R.A., Bruland A., Jakobsen P.D., Lohne J., (2015), Environmental impact of drill and blast tunnelling: life cycle assessment, *Journal of Cleaner Production*, **86**, 110-117.

Hwang Y.W., Park K.H., Seo S.W., (2000), Assessment of CO_2 emissions from road construction activities, *Journal of the Korean Society of Civil Engineers*, **31**, 113-121.

Imura H., (2013), *Kensetsu no LCA* (in Korean), CIR Communication, Seoul, Republic of Korea.

Jeong K., Ji C., Koo C., Hong T., Park, H.S., (2015), A model for predicting the environmental impacts of educational facilities in the project planning phase, *Journal of Cleaner Production*, **107**, 538-549.

Junnila S., Horvath A., (2003), Life-cycle environmental effects of an office building, *Journal of Infrastructure Systems*, **9**, 157-166.

KEITI, (2016), Korea LCI database information network, On line at: http://www.epd.or.kr/lci/lci_intro.asp.

Liu C., Ahn C., An X., Lee S., (2013), Life-cycle assessment of concrete dam construction: comparison of environmental impact of rock-filled and conventional concrete, *Journal of Construction Engineering and Management*, **139**, A4013009.

MCIE, (2003), Environmental management standardization project for environment-friendly industry, Ministry of Commerce Industry and Energy, Sejong City, Republic of Korea.

Min S.Y., Kim T.K., Lee J.S., Einstein H. H., (2008), Design and construction of a road tunnel in Korea including application of the decision aids for tunneling – a case study, *Tunneling and Underground Space Technology*, **23**, 91-102.

MOCT, (2003), The Study of LCA application schemes on Construction industry areas, (in Korean), Ministry of Construction and Transportation, Sejong City, Republic of Korea..

Moon H.S., Hyun C.T., Hong T.H., (2014), Prediction model of CO_2 emission for residential buildings in South Korea, *Journal of Management in Engineering*, **30**, doi:10.1061/(ASCE)ME.1943-5479.0000228, 04014001.

MOTI, (2013), Project cost estimating guidelines, Ministry of Transportation and Infrastructure, Victoria BC, Canada.

Onofrei M., Dascalu E.D., Roman A., Bogdan-Narcis Firtescu B.-N., (2018), The impact of environmental tax reform on greenhouse gas emissions: empirical evidence from European countries, *Environmental Engineering and Management Journal*, **17**, 2843-2849.

Piratla K., Ariaratnam S., Cohen A., (2012), Estimation of CO_2 emissions from the life cycle of a potable water pipeline project, *Journal of Management in Engineering*, **28**, 22-30.

Schank R., Abelson R., (1977), *Scripts, Plans, Goals and Understanding*, Erlbaum, Hillsdale, NJ, USA.

van Geldermalsen L.A., (2004), *Environmental Aspects in Tunnel Design*, 1st Int. Symp. on Safe and Reliable Tunnels, Innovative European Achievements, Prague, 199-210.

Verbitsky O., Pushkar S., (2018), Eco-indicator 99, Recipe and Anova for evaluating building technologies under LCA uncertainties, *Environmental Engineering and Management Journal,* **17**, 2549-2559.