JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730 / eISSN 1822-3605
2016 Volume 22(1): 73–85
doi:10.3846/13923730.2014.897964

CONFIGURATION OF EARTHWORK EQUIPMENT CONSIDERING ENVIRONMENTAL IMPACTS, COST AND SCHEDULE

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Received 05 Jul 2012; accepted 22 Mar 2013

Abstract. Along with promotion of public awareness about sustainability, the concept of sustainability has gained increasing attention across all industries. The construction industry is one of the largest industries, and at the same time, among the largest polluters. Thus, the concept of sustainability has become increasingly important to construction firms and many contractors have started to reduce the environmental impacts of their construction activities. As part of the effort to achieve sustainability in construction sector, the study develops a method to select earth-moving equipment, based on their environmental impacts as well as duration and cost considerations. To this end, the study initially develops a model for determining construction costs and duration as well as a model for determining monetary environmental impacts on earthwork construction. The study then uses an Improved Weight Decision Method (IWDM) to determine the weight of variables in order to find the best performed equipment configuration. The authors expect that the findings of the study will contribute to the research and practice in configuring earthwork equipment, taking into account associated environmental impacts as well as time and costs.

Keywords: earthwork equipment, environmental impacts, equipment configuration, improved weight decision method (IWDM).

Introduction

Background

The construction industry is one of the largest and most important industries. It is, however, among the largest polluters too (Bae, Kim 2008). Over the last decade, sustainability has become increasingly important to construction firms and many contractors currently make extensive efforts to reduce environmental impacts of their construction activities. Movement towards sustainability leads to a shift of construction paradigm to incorporate the environmental factors in various managerial decisions.

The endogenous CO_2 emissions are mainly from construction equipment powered with fossil fuel combustion in most heavy civil construction activities (Frey *et al.* 2008). Configuration of earthwork equipment in heavy civil construction projects is made taking into account various factors, such as attributes of site condition and schedule tightness. How well the earthwork equipment is configured is critical in earthwork construction. However, few studies have investigated earthwork equipment configuration taking into account environmental impacts.

Research objectives, scope and method

The main objective of this research is to propose a decision-making method in equipment configuration. This method is based on selection of a combination of earthmoving equipment considering their monetary environmental impacts as well as construction duration and costs. To achieve its objective, the study uses a hypothetical case study with following assumptions:

- The scope of the project in the case study is to move 100,000 m^3 of soil;
- The type of the soil to be moved is well-graded sand with clay;
- The dumping area is assumed to be located 500 meters away from the spot;
- Analysis of the environmental impacts is limited to energy consumption and emissions associated with operation of construction equipment.

The study first develops a model for determining construction costs and duration as well as a model for determining monetary environmental impacts on earthwork construction. The model for construction costs addresses operational costs as well as rents based on the operation hours calculated by a discrete-event simulation program

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(i.e. EZstrobe). Construction costs estimated in this research are based on daily rents for eight hours per day as well as monthly rents for twenty-five days per month. Monthly rents are applied to dozers while daily rents are used for other types of heavy equipment.

The model for determining environmental impacts is developed based on the life-cycle analysis methodology for energy consumption and emission, as suggested by ISO 14040 (1997). The study then uses contingency valuation method (CVM), converting the amount of willing-to-pay (WTP) for each unit of damage per standard material into environment costs (Kwon 2008; Moon 2009). Later, an Improved Weight Decision Method (IWDM) is used to determine the weights of variables to figure out the best equipment configuration.

1. Relevant research

1.1. Equipment configuration and economic value of environmental factors

Earthwork equipment configuration has a significant impact not only on construction performances (i.e. schedule and costs) but also on the environment. Few studies have investigated the relationship between earthwork equipment configuration and environmental impacts. Li *et al.* (2011) measured the endogenous CO_2 emission in tunnel construction projects in Western China. Hwang *et al.* (2000) estimated CO_2 emission for different processes on highway construction using CO_2 emission coefficient per unit work of each construction equipment. Hwang *et al.* (2000) showed that CO_2 emission from earthwork in road construction amounts to around 94.5%. Hwang *et al.* (2000) showed that dump trucks and dozers emit tremendous amount of CO_2 in highway construction. The report suggests that effective configuration of earthwork equipment can lead to significant reduction in greenhouse gas emissions.

Kwon (2008) presented an assessment model for evaluating environmental economics that can be applied to all types of construction projects. This assessment model in line with ISO 14040 (1997) is applied in this article to estimate the environmental impacts.

1.2. Multi-attribute selection techniques

Many decisions are based on other attributes than price. Multi-attribute selection problems are referred to multi-attribute decision making (MADM) with discrete, usually limited, number of pre-specified alternatives, requiring inter and intra-attribute comparison involving tradeoffs as in equipment selection problem (Hwang, Yoon 1981; Zanakis *et al.* 1998). Several methods have been proposed for solving multi-attribute selection problems.

Multi-attribute utility theory (MAUT) combines a class of psychological measurement models and scaling procedure that can be applied to the evaluation of alternatives with multiple value relevant attributes. MAUT theories are used extensively in policy analysis where decisions are sensitive to not only economic costs but also more subjective goals such as environmental concerns (Kim *et al.* 1998; Hassan 2008). Simple multi-attribute rating technique (SMART) is the simplest form of the MAUT methods. The ranking value xj of alternative Aj is obtained simply as the weighted algebraic mean of the utility values associated with it (Edwards 1977). The analytic hierarchy process (AHP) has also been used widely to solve problems having multiple criteria (Saaty 2008). The purpose of using AHP is to determine relative ranking of the decision alternatives. To use AHP, the decision maker(s) must compare all pairs of criteria and decision alternatives using a ratio scale. The accuracy of these comparisons depends on information available to the decision maker(s) as well as on the decision maker(s) depth of understanding of the problem under consideration (Levary, Wan 1998). The Improved Weight Decision Method (IWDM) is a weighting-assigning utility method which proved to be suitable and easily used with a small number of attributes (Shon 2000). The research adopted the IWDM because the method is simple and the number of attributes is limited to three.

2. Calculation of costs, time, and environmental costs

2.1. Construction costs

To calculate the costs of equipment configuration, two assumptions were made: (1) hourly rental fees were assumed based on eight working hours per working day, and (2) monthly rental fees were assumed based on 25 working days per month. Also, it was assumed that dozers are rented monthly while others are rented daily. The rental fee on earthwork equipment from Monthly Trade Price Association (2010) was used in this study.

2.2. Construction duration

Construction duration depends mainly on how earthwork equipment is configured. While many publications use a critical path method to calculate construction duration, the authors used the MicroSoft EZstrobe program, a discrete-event simulation program. EZstrobe program (2011) uses activity cycle diagram which allows users to develop a discrete-event simulation model without coding.

2.3. Environmental costs

The analysis categorized various environmental impacts of major construction materials into eight areas at the classification stage. As characterization stage is the process of quantifying the impacts of each inventory classified, the characterization result's values are calculated by the product of equivalency factor, g-eq/g of inventory, and environmental load of each inventory.

The normalization result values are calculated by multiplying normalization standard values (the Ministry of Knowledge Economy in Korea 2010) by the characterization result's values in order to unify a unit of each impact. The weighting result values are then obtained by multiplying weighting standard values (the Ministry of Knowledge Economy in Korea 2010) by the normalization result values.

The quantity of environmental impacts of diesel is calculated through the procedures mentioned above. The weighted values of the environmental impact factors for major construction materials are shown in Table 1 (Moon 2009).

The environmental expenses per pollutant emission (ton) in this study are calculated based on Kwon (2008) which suggests converting the willingness to pay (WTP) per damaged unit by standard substance into environmental expenses (Table 2). Kwon (2008) used the Contingent Valuation Method (CVM) based on the Multi-Attribute Utility Theory (MAUT) to convert WTP to environmental expenses. The Contingent Valuation Method (CVM) is a method that directly draws a value which people assign to any public goods or environmental goods, quantifying the environmental impacts of a construction business through willingness to pay (WTP).

2.4. Proposed model for earthwork equipment configuration

Configuration of earthwork equipment affects the construction costs and time as well as the environmental impacts. The proposed model for earthwork equipment configuration consists of three parts: (1) duration and costs using discrete event simulation, (2) environmental costs using environmental impact factor, and (3) assessment of equipment combination as shown in Figure 1. Details on each process are addressed in the following sections.

2.5. Possible combinations of equipment

The first stage is to figure out possible combinations of earthwork equipment, each of which defines soil and site conditions, distances, and earthwork quantities as shown in Table 3. Although the types of equipment are various, the research assumed sixteen combinations of earthwork equipment based on the popularity of those types of equipment on sites. The number of dozers was limited to two due to spatial restrictions while others did not have such spatial restrictions. Equipment combinations used in the study are shown in Table 4. The study further subcategorized equipment combinations into sub-combinations depending on the number of equipment on each combination. Table 5 shows an example of sub-combinations in combination #1.

The discrete-event simulation requires determination of the input variables. Input variables in the simulation model include cycle time (i.e. duration of activity) of each type of equipment considering working conditions, equipment types, and work quantity. The 2010 Construction Work's Standard of Estimation (Korea Construction Promotion Association 2010) was used to determine input variables for simulation such as workload per hour and cycle time of equipment. In addition, this study used the Standard of Estimation (Korea Construction Promotion Association 2010) in determining the transportation distance coefficient and other coefficients such as working efficiency.

2.6. Computation of construction period and expenses

The construction period was calculated by using the EZstrobe Simulation. In addition, construction expenses were computed on the basis of rental fees per hour (Korea Construction Promotion Association 2010) and based

Table 2. Costs of environmental impact factors (source: Kwon 2008)

No.	Environmental Impact Factor	Cost (USD $)/Ton
1	Abiotic Resources Depletion	287.3
2	Global Warming	51.5
3	Ozone Depletion	145.9
4	Photochemical Oxidant Creation	21.0
5	Acidification	59.8
6	Eutrophication	1.1
7	Eco Toxicity	0.8
8	Human Toxicity	64.1

Table 1. Weighted values for major construction material (ton-eq/ton) (source: Moon 2009)

No.	Environmental Impact Factor	Ready mixed concrete	Cement	Asphalt concrete	Reinforce	Section Steel	Diesel Oil
1	Abiotic Resources Depletion	1.03E+01	9.71E+00	1.32E-03	9.78E-03	1.22E-02	1.90E-04
2	Global Warming	6.83E+05	1.69E+06	2.52E+01	6.98E+02	6.83E+02	6.10E-01
3	Ozone Depletion	5.47E-07	4.23E-07	8.51E-11	1.26E-10	3.40E-10	1.52E-11
4	Photochemical Oxidant Creation	1.71E+01	1.23E-01	1.96E-02	1.49E-04	1.09E-04	1.27E-07
5	Acidification	1.01E+00	5.73E-01	9.59E-06	2.01E-03	1.91E-03	1.24E-06
6	Eutrophication	3.70E-04	6.02E-05	6.07E-08	4.95E-07	4.66E-07	6.32E-09
7	Eco Toxicity	1.19E+00	6.59E-01	1.84E-04	3.65E-04	8.73E-04	1.32E+00
8	Human Toxicity	2.22E+02	4.20E+02	4.20E+02	2.27E-01	2.42E-01	2.27E-02
Sum		6.83E+05	1.69E+06	4.45E+02	6.98E+02	6.83E+02	1.95E+00

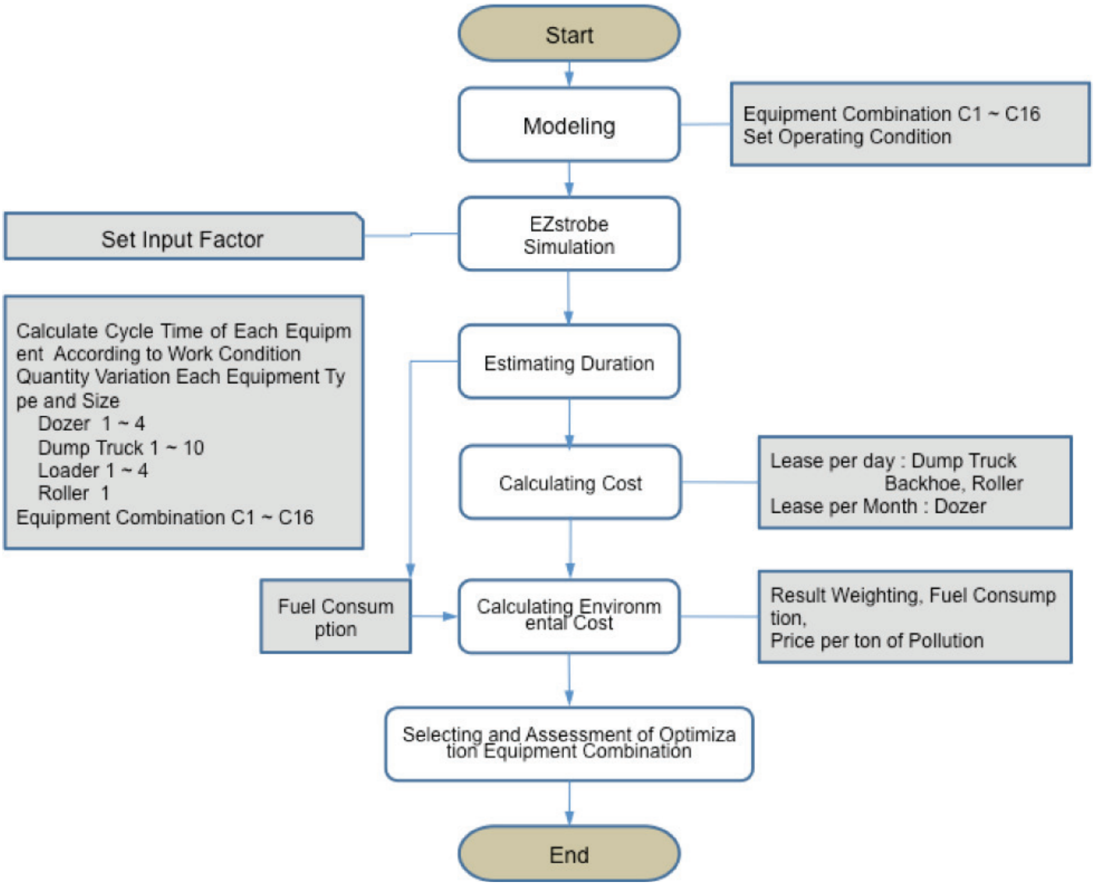

Fig. 1. Modelling procedure for selecting earthwork equipment

Table 3. Soil conditions as input variables

Condition	Soil Quality	Work Condition	Distance (m)	Quantity (m^3)	Number of Equipment Combination
Condition A	Sand, Sand Soil	Natural State (good)	500	100,000	16
Condition B	Gravel Soil, Clay	Natural State (bad)	500	100,000	16

on equipment utilization time resulting from the EZstrobe simulation result. Figure 2 shows the EZstrobe Simulation model of equipment combination. For the purpose of simulation, earthwork was divided into five (5) types of activities: excavation, loading, transport, compaction and inspection.

Figures 3 and 4 show the relationship between construction period and construction expenses on various equipment combinations. As shown in Figure 3, the subcombination #13, which appeared to be the most advantageous in terms of the construction period, is the most advantageous even in terms of construction expenses. However, the case of the equipment combination #2 shows a different result than that of the combination #1. Figure 4 shows the result of the equipment combination #2, and even though the detailed combination #13 is the most advantageous among detailed combinations using less than 2 dozer units, it appeared that the advantageous combination in construction expenses is the detailed combination #10. On the other hand, the most advantageous combination in construction period and expenses is detailed combination #21 which is composed of 4 dozers, 6 back hoes, 7 trucks and one vibration roller. If field conditions being taken into account, the detailed combination #21 is excluded because it is unrealistic.

Table 6 summarizes the results of construction period and expenses calculated based on the equipment combinations. Combinations (1–8) with high capacity dozer (32T) showed reduced duration compared to combinations (9–16) with low capacity dozer (19 ton). The most advantageous combination with respect to construction period and expenses in the case of condition A is combination #1 while the best combination in the case of condition B is combination #2. Namely, dozer 32 ton, back hoe 1.0 m^3, dump truck 15 ton and roller 10 ton are most advantageous, when the field condition is favourable like condition A. When working conditions are disadvantageous

Table 4. Equipment combinations by its type and size

Combination	Excavation	Load	Transportation	Compact
Combination 1	Dozer (32T)	Backhoe (1.0 m^3)	Dump Truck (15T)	Vibration Roller (10T)
Combination 2			Dump Truck (24T)	
Combination 3		Backhoe (0.8 m^3)	Dump Truck (15T)	
Combination 4			Dump Truck (24T)	
Combination 5		Backhoe (0.7 m^3)	Dump Truck (15T)	
Combination 6			Dump Truck (24T)	
Combination 7		Backhoe (0.6 m^3)	Dump Truck (15T)	
Combination 8			Dump Truck (24T)	
Combination 9	Dozer (19T)	Backhoe (1.0 m^3)	Dump Truck (15T)	
Combination 10			Dump Truck (24T)	
Combination 11		Backhoe (0.8 m^3)	Dump Truck (15T)	
Combination 12			Dump Truck (24T)	
Combination 13		Backhoe (0.7 m^3)	Dump Truck (15T)	
Combination 14			Dump Truck (24T)	
Combination 15		Backhoe (0.6 m^3)	Dump Truck (15T)	
Combination 16			Dump Truck (24T)	

Table 5. Sub-combinations of combination #1

Sub-Combination	Quantity Each Equipment Type			
No	Dozer (32 ton)	Backhoe (1.0 m^3)	Dump Truck (15 ton)	Roller (10 ton)
1	1	1	1	1
2	1	1	2	1
3	1	1	3	1
4	1	2	2	1
5	1	2	3	1
6	1	2	4	1
7	1	3	3	1
8	1	3	6	1
9	2	2	2	1
10	2	2	3	1
11	2	2	4	1
12	2	2	6	1
13	**2**	**3**	**4**	**1**
14	2	3	5	1
15	2	3	6	1
16	2	4	8	1
17	2	6	10	1
18	3	6	12	1
19	4	8	16	1

like condition B, dozer 19 ton, back hoe 0.7 m^3, dump truck 15 ton and roller 10 ton are advantageous. Small-sized equipment is usually advantageous when the field condition is not favourable. However, the results were not affected by the size of equipment in the case of a dump truck regardless of the field condition. This is because the transport distance was comparatively short (500 m). In other words, 24 ton dump truck becomes more advantageous in longer transport distances.

2.7. Computation of energy consumption

In order to calculate the energy consumption, the energy consumption per hour was utilized as suggested by the Standard of Estimation. Energy consumption can be calculated by multiplying fuel consumption by equipment operation hours. The energy consumption per hour by equipment is shown in Table 7.

The actual operation hours and waiting hours by equipment were calculated by using workload per hour

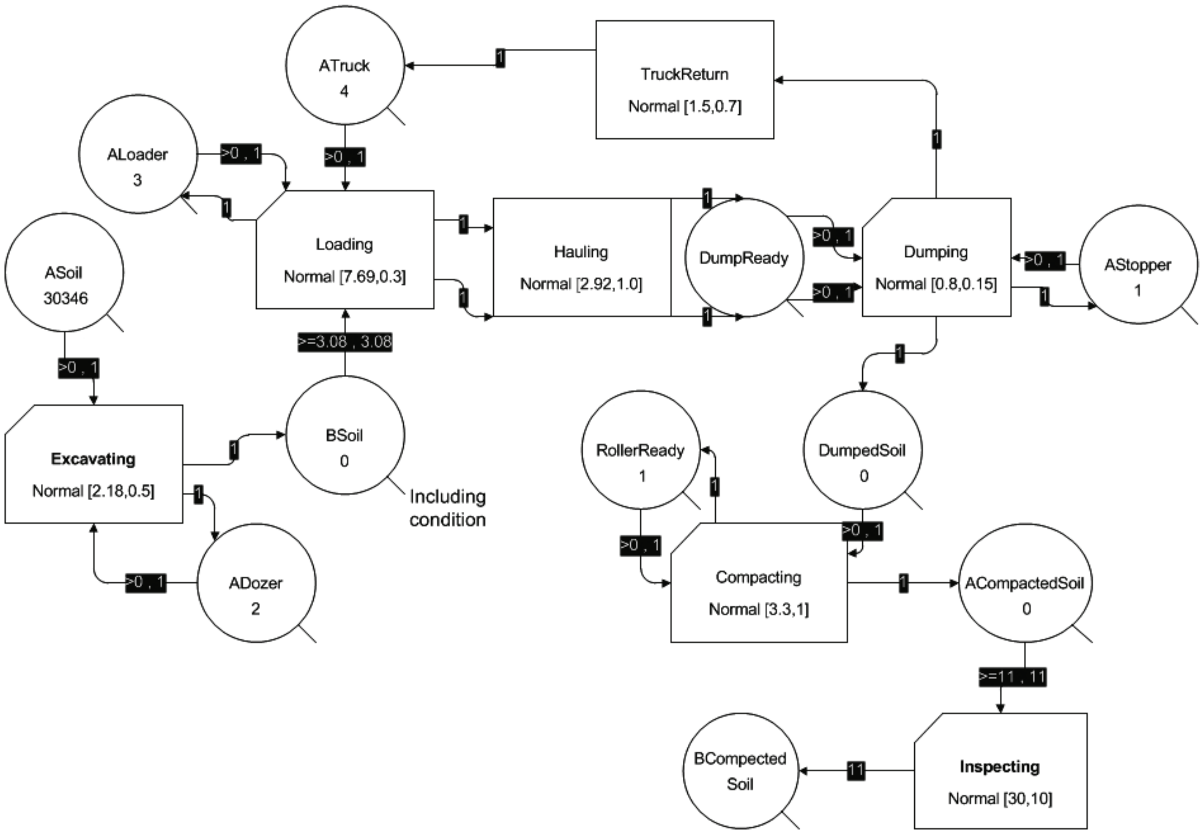

Fig. 2. EZstrobe simulation example of equipment 1

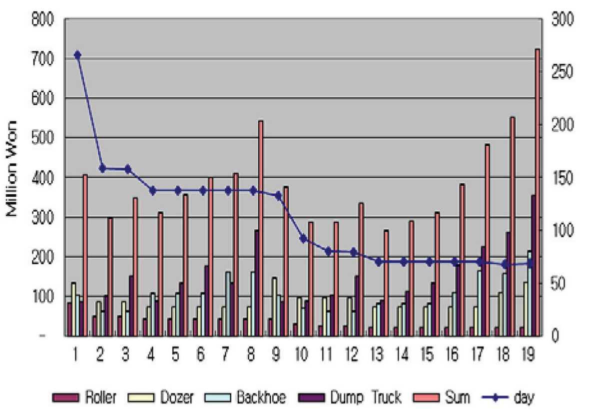

Fig. 3. Duration and cost of equipment combination 1

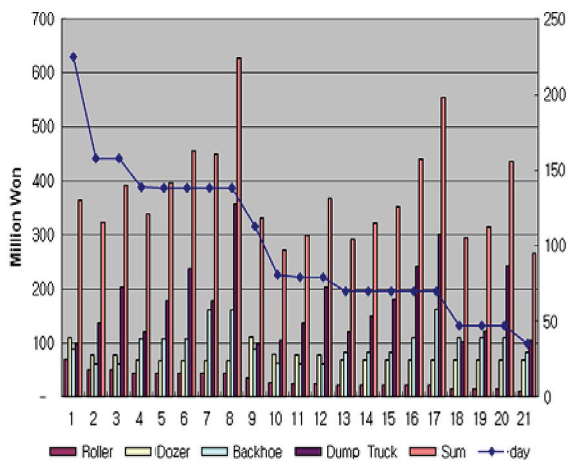

Fig. 4. Duration and cost of equipment combination 2

of equipment, as shown in Table 8. The energy consumption by equipment has been shown in Tables 9 and 10.

2.8. Computation of total environmental expenses

The total environmental expenses are calculated using the Eqn (1). The environmental impact and expenses assessed based on the fuel consumption by equipment combinations, are the same as in the ones shown in Tables 10 and 11. The field conditions of Tables 10 and 11 are condition A and condition B, respectively. Conditions A and B are defined in Table 3.

$$Ecost = \sum_{i=1}^{n} (Ecu \times EIFw \times DOc), \qquad (1)$$

where: Ecost is the total environmental cost (USD \$); n – the number of environmental impact factor; Ecu – unit environmental cost (USD \$); $EIFw$ – weigted environmental impact factor; (ton-eq/ton); DOc – the diesel consumption (ton).

Table 6. Result of duration and cost each equipment combination

Combination	Condition A		Condition B	
	Cost (USD $)	Duration (days)	Cost (USD $)	Duration (days)
Comb. 1	241,991	**70**	445,858	156
Comb. 2	247,050	81	422,795	**159**
Comb. 3	273,955	70	481,853	166
Comb. 4	286,027	70	528,061	161
Comb. 5	297,736	70	518,753	156
Comb. 6	324,358	78	593,925	186
Comb. 7	307,409	70	546,265	156
Comb. 8	322,045	70	567,807	164
Comb. 9	285,167	116	468,964	260
Comb. 10	274,622	116	520,964	260
Comb. 11	302,884	116	600,382	260
Comb. 12	337,684	116	652,382	260
Comb. 13	303,721	121	580,527	260
Comb. 14	328,825	116	632,527	260
Comb. 15	338,103	137	565,388	263
Comb. 16	360,884	116	612,673	260

The analysis has eight (8) environmental impact factors in the Eqn (1) (i.e. $n = 8$) as being suggested in Tables 1 and 2. In the case of the unit environmental expenses (Ecu), the expenses per ton, according to an environmental impact factor, are shown in Table 2. The analysis uses the "Diesel Oil" weighted value (ton-eq/ton) for the weighted environmental impact factors (EIFw) shown in Table 1. Diesel consumption refers to fuel consumption according to equipment combination, and is calculated based on fuel consumption by equipment suggested in Tables 9 and 10. Table 11, for example, shows the calculation process of total environmental costs for combination #1 under condition A using the Eqn (1).

Total environmental expenses calculated suggest that the combination with the least CO_2 emission is combination #6 in Tables 12 and 13. The equipment combination #6 is made up of 32 ton dozer, 0.7 m^3 back hoe, 24 ton dump truck and 10 ton vibration roller. In the case of condition A, it is made up of two dozers, three backhoes, four trucks and one roller, and in the case of condition B, it is made up of two dozers, two backhoes, three trucks, and one roller, respectively.

Table 7. Fuel consumption per hour each equipment size

Division	Dozer		Back hoe				Dump Truck			Roller
	32 ton	19 ton	1.0 m^3	0.8 m^3	0.7 m^3	0.6 m^3	15 ton	24 ton	Waiting Time	10 ton
Fuel Consumption (per hr)	41.6	25.0	19.5	15.3	11.6	10.2	15.9	23.0	1.5	14.4

Note: fuel consumption per hour is calculated by load factor 70~80% and real work time 50/60 (Standard of Estimate 2010).

Table 8. Work and waiting time (hour)

Division	Dozer		Back hoe				Dump Truck				Roller
	32 ton	19 ton	1.0 m^3	0.8 m^3	0.7 m^3	0.6 m^3	15 ton		24 ton		10 ton
							Work	Waiting	Work	Waiting	
Condition A	1,103	1,843	1,263	1,578	1,804	2,104	735	1,974	459	1,839	543
Condition B	2,487	4,155	2,058	2,575	2,939	3,429	756	3,552	473	3,356	119

Table 9. Energy consumption of equipment (Condition A)

Division	Dozer		Back hoe				Dump Truck				Roller
	32 ton	19 ron	1.0 m^3	0.8 m^3	0.7 m^3	0.6 m^3	15 ton		24 ton		10 ton
							Work	Waiting	Work	Waiting	
Energy Consumption (L)	45,872	46,063	24,621	24,148	20,924	21,465	11,680	2,922	10,557	2.722	7,816
Unit Weight of Diesel	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Energy Consumption (ton)	38.07	38.23	20.44	20.04	17.37	17.82	9,69	2.43	8.76	2.26	6.49

Table 10. Energy consumption of equipment (Condition B)

Division	Dozer		Back hoe				Dump Truck				Roller
							15 ton		24 ton		
	32 ton	19 ron	1.0 m^3	0.8 m^3	0.7 m^3	0.6 m^3	Work	Waiting	Work	Waiting	10 ton
Energy Consumption (L)	103,456	103,886	40,123	39,352	34,098	34,979	12,020	5,257	10,870	4,967	12,115
Unit Weight of Diesel	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Energy Consumption (ton)	85.87	86.23	33.30	32.66	28.31	29.03	9.98	4.36	9.02	4.12	10.06

Table 11. Total environmental cost calculation process for combination #1

No	Env. Impact Factor	EIFx * (1)	EIFx x Doc** (2)	Cost/ton (3)	EnC*** (4)
1	Abiotic Resources Depletion	1.90E-04	1.47E-02	287	4.21
2	Global Warming	6.10E-01	4.70E+01	51	2422.27
3	Ozone Depletion	1.52E-11	1.17E-09	146	0.00
4	Photochemical Oxidant Creation	1.27E-07	9.79E-06	21	0.00
5	Acidification	1.24E-06	9.56E-05	60	0.01
6	Eutrophication	6.32E-09	4.87E-07	1	0.00
7	Eco Toxicity	1.32E+00	1.02E+02	1	85.97
8	Human Toxicity	2.27E-02	1.75E+00	64	112.17
	Sum	1.95E+00	1.51E+02		2624.62

Note: * From a column of "Diesel" in Table 1;
** Column (1) × Table 2;
*** Column (2) × Table 3.

Table 12. Environmental cost according to fuel consumption of equipment combination (Condition A)

Equipment Combination	comb. 1	comb. 2	comb. 3	comb. 4	comb. 5	comb. 6	comb. 7	comb. 8
Fuel Consumption (ton)	77.1	76.0	77.2	76.1	74.9	**73.8**	75.8	74.7
Env. Cost (USD $)	2,625	2,587	2,628	2,591	2,549	2,512	2,580	2,543
Equipment Combination	comb. 9	comb. 10	comb. 11	comb. 12	comb. 13	comb. 14	comb. 15	comb. 16
Fuel Consumption (ton)	77.3	76.2	77.4	76.3	75.1	74.0	76.0	74.9
Env. Cost (USD $)	2,630	2,593	2,634	2,596	2,555	2,517	2,585	2,548

2.9. Assessment of optimal equipment combination

It is necessary to convert the assessment criteria (cost, duration and environmental costs) with different units into a single unit in order to select the optimal equipment combination. Accordingly, a relative index of each value is used as a tool for that purpose. Namely, numerical values in different units are converted to relative index as shown in Tables 12 and 13, assuming the values of combination #1 to 10. All relative index values represent ratio of real value of each combination to that of combination #1. The field conditions of Tables 14 and 15 are condition A and condition B, respectively.

The weight in this research is utilized as a method to comprehensively assess construction duration, expenses, and environmental expenses. The research uses the Improved Weight Decision Method (IWDM) (Shon 2000), as weight-assigning method, which can be suitable and easily used when the number of items is small. The method begins with determining the relative weight of each assessment criteria, which represents the relative importance of each criteria to decision makers. Several methods including focus group interview could be used to determine relative weight of each criteria. The values (3, 2, and 1) in Table 16 are randomly

Table 13. Environmental cost according to fuel consumption of equipment combination (Condition B)

Equipment Combination	comb. 1	comb. 2	comb. 3	comb. 4	comb. 5	comb. 6	comb. 7	comb. 8
Fuel Consumption (ton)	143.6	142.4	143.9	142.7	140.2	139.0	141.8	140.6
Environmental Cost (thousand won)	4,886	4,845	4,896	4,855	4,770	4,730	4,825	4,785
Equipment Combination	comb. 9	comb. 10	comb. 11	comb. 12	comb. 13	comb. 14	comb. 15	comb. 16
Fuel Consumption (ton)	143.9	142.7	144.2	143.0	140.5	139.3	142.1	140.9
Environmental Cost (thousand won)	4,898	4,857	4,908	4,867	4,783	4,742	4,837	4,796

Table 14. Assessment of each combination using relative index (Condition A)

Combination	Real Value			Relative Index			Sum (A)+(B)+(C)
	Construction Cost (USD$)	Duration (day)	Environment Cost (USD$)	Construction Cost Rate (A)*	Duration Rate (B)**	Environment Cost Rate (C)***	
Comb. 1	241,991	70	2,625	**10.00**	**10.00**	10.00	**30.00**
Comb. 2	247,050	81	2,587	10.21	11.57	9.86	31.64
Comb. 3	273,955	70	2,628	11.32	**10.00**	10.01	31.33
Comb. 4	286,027	70	2,591	11.82	**10.00**	9.87	31.69
Comb. 5	297,736	70	2,549	12.30	**10.00**	9.71	32.02
Comb. 6	324,358	78	2,512	13.40	11.14	**9.57**	34.12
Comb. 7	307,409	70	2,580	12.70	**10.00**	9.83	32.53
Comb. 8	322,045	70	2,543	13.31	**10.00**	9.69	33.00
Comb. 9	285,167	116	2,630	11.78	16.57	10.02	38.38
Comb. 10	274,622	116	2,593	11.35	16.57	9.88	37.80
Comb. 11	302,884	116	2,634	12.52	16.57	10.03	39.12
Comb. 12	337,684	116	2,596	13.95	16.57	9.89	40.42
Comb. 13	303,721	121	2,554	12.55	17.29	9.73	39.57
Comb. 14	328,825	116	2,517	13.59	16.57	9.59	39.75
Comb. 15	338,103	137	2,586	13.97	19.57	9.85	43.40
Comb. 16	360,884	116	2,549	14.91	16.57	9.71	41.19

Note: * Construction Costs / 241,991 × 10;
** Duration / 70 × 10;
*** Environmental Costs / 2,625 × 10.

selected to demonstrate the proposed method. The IWDM technique is a method that calculates the weight by accumulating the size of relative importance among the items where the weight of the least important factor is one (1). Resulting weight refers to a ratio of cumulative weight to total cumulative weight. The weight for each can be calculated as shown in Table 16 where environmental expenses were considered to be the most important.

It is necessary to use relative difference of indexes using weight. The research uses relationships between indexes for items and their weights on the grounds of the idea that the difference between indexes should be corrected as much as the size of weight. Tables 17 and 18 show relative weight's correction process, the results of which are shown in Table 16 different from the results shown in Tables 14 and 15.

The calculation process and equation used in Table 17 are as follows:

Step 1. *Calculate relative difference by weight*:

$$RDWcc(n) = (RIcc(n) - RIcc(1)) \times Wcc; \quad (2)$$

$$RDWd(n) = (RId(n) - RId(1)))) \times Wd; \quad (3)$$

$$RDWec(n) = (RIec(n) - RIec(1)) \times Wec, \quad (4)$$

where: RDWcc(n) – Relative Difference by Weight of construction cost (combination n); RIcc(n) – Relative Index of construction cost of combination n; RIcc(1) –

Table 15. Assessment of each combination using relative index (Condition B)

Combination	Real Value			Relative Index			Sum (A)+(B)+(C)
	Construction Cost (USD$)	Duration (day)	Environment Cost (USD$)	Construction Cost Rate (A)	Duration Rate (B)	Environment Cost Rate (C)	
Comb. 1	445,858	156	4,886	10.00	**10.00**	10.00	30.00
Comb. 2	422,795	159	4,846	**9.48**	10.19	9.92	**29.59**
Comb. 3	481,853	166	4,896	10.81	10.64	10.02	31.47
Comb. 4	528,061	161	4,855	11.84	10.32	9.94	32.10
Comb. 5	518,753	156	4,770	11.63	**10.00**	9.76	31.40
Comb. 6	593,925	186	4,730	13.32	11.92	**9.68**	34.92
Comb. 7	546,265	156	4,825	12.25	**10.00**	9.88	32.13
Comb. 8	567,807	164	4,785	12.74	10.51	9.79	33.04
Comb. 9	468,964	260	4,898	10.52	16.67	10.02	37.21
Comb. 10	520,964	260	4,858	11.68	16.67	9.94	38.29
Comb. 11	600,382	260	4,908	13.47	16.67	10.05	40.18
Comb. 12	652,382	260	4,868	14.63	16.67	9.96	41.26
Comb. 13	580,527	260	4,783	13.02	16.67	9.79	39.47
Comb. 14	632,527	260	4,742	14.19	16.67	9.70	40.56
Comb. 15	565,388	263	4,838	12.68	16.86	9.90	39.44
Comb. 16	612,673	260	4,797	13.74	16.67	9.82	40.22

Table 16. Assigning weights

Division	Relative Weight	Cumulative Weight*	Resulting Weight
Environmental Cost	3	6 = 3 × 2	0.67 (=6/9)
Duration	2	2 = 2 × 1	0.22 (=2/9)
Construction Cost	1	1	0.11 (=1/9)
Sum		9	1.00

Note: *Cumulative weight (i) = Relative weight (i) × Cumulative weight (i-1).

Relative Index of construction cost of combination 1; Wcc – Weight of construction cost.

The results of this phase show the differences of combinations converted into relative index on the basis of combination 1.

Step 2. *Calculate the relative difference calibrated index*:

$$ICRDcci(n) = RDWcc(n) + RIcc(1); \quad (5)$$

$$ICRDdi(n) = RDWd(n) + RId(1); \quad (6)$$

$$ICRDeci(n) = RDWec(n) + RIec(1), \quad (7)$$

where: ICRDcci(n) – Difference of construction cost calibrated index (combination n).

Step 3. *Calculate the weight calibrated index*:

$$ICWcci(n) = ICRDcci(n) \times Wcc; \quad (8)$$

$$ICWdi(n) = ICRDdi(n) \times Wd; \quad (9)$$

$$ICWeci(n) = ICRDeci(n) \times Wdc, \quad (10)$$

where: ICWcci(n) – Weight of construction cost calibrated index (combination n).

The ICW is calculated by multiplying the weight by the value calculated in the phase two.

Step 4. *Calculate the calibrated index lastly*:

$$\text{Revised Index } (n) = \{ICWcci(n) + ICWdi(n) + ICWeci(n)\}\ i(n)\}. \quad (11)$$

Figures 5 and 6 are graphs showing the correction indexes computed by a relative difference correction technique of indexes where weight is considered on different scenarios. A-3 shows the assessment results when the users assumed environmental expenses as the most important criteria. A-1 and A-2 show the assessment results when construction expenses and construction duration, respectively, were assumed the most important criteria. Though equipment combination #1 seems the most advantageous in graphs A-1 and A-2, equipment combination #5 appears the most advantageous in case of A-3. The result suggests that the best equipment combination can be varied according to user-defined criteria.

The results in condition A are in line with the ones in condition B (gravel-mixed soil, cohesive soil and badness of field conditions). B-3 shows the assessment results when users assumed environmental expenses as the most important criteria. B-1 and B-2 show the assessment results when construction expenses and construction duration, respectively, are assumed the most

Table 17. Assessment of calibrated index (Condition A)

Equipment Combination	RDW (Relative Difference by Weight)			ICRD (Relative Difference Calibrated Index)			ICW (Weight Calibrated Index)			{(A)+(B)+(C)} ×100 Revised Index
	Const. Cost (A)	Duration (B)	Envnt. Cost (C)	Const. Cost Index (A)	Duration Index (B)	Envnt. Cost Index (C)	Const. Cost Index (A)	Duration Index (B)	Envnt. Cost Index (C)	
Comb. 1	0.00	0.00	0.00	10.00	10.00	10.00	1.11	2.22	6.67	1,000.00
Comb. 2	0.02	0.35	–0.09	10.02	10.35	9.91	1.11	2.30	6.60	1,001.79
Comb. 3	0.15	0.00	0.01	10.15	10.00	10.01	1.13	2.22	6.67	1,002.07
Comb. 4	0.20	0.00	–0.09	10.20	10.00	9.91	1.13	2.22	6.61	996.47
Comb. 5	0.26	0.00	–0.19	10.26	10.00	9.81	1.14	2.22	6.54	989.95
Comb. 6	0.38	0.25	–0.29	10.38	10.25	9.71	1.15	2.28	6.48	990.72
Comb. 7	0.30	0.00	–0.11	10.30	10.00	9.89	1.14	2.22	6.59	995.78
Comb. 8	0.37	0.00	–0.21	10.37	10.00	9.79	1.15	2.22	6.53	990.31
Comb. 9	0.20	1.46	0.01	10.20	11.46	10.01	1.13	2.55	6.68	1,035.53
Comb. 10	0.15	1.46	–0.08	10.15	11.46	9.92	1.13	2.55	6.61	1,028.78
Comb. 11	0.28	1.46	0.02	10.28	11.46	10.02	1.14	2.55	6.68	1,036.89
Comb. 12	0.44	1.46	–0.07	10.44	11.46	9.93	1.16	2.55	6.62	1,032.43
Comb. 13	0.28	1.62	–0.18	10.28	11.62	9.82	1.14	2.58	6.55	1,027.15
Comb. 14	0.40	1.46	–0.27	10.40	11.46	9.73	1.16	2.55	6.48	1,018.65
Comb. 15	0.44	2.13	–0.10	10.44	12.13	9.90	1.16	2.69	6.60	1,045.49
Comb. 16	0.55	1.46	–0.19	10.55	11.46	9.81	1.17	2.55	6.54	1,025.62

Table 18. Assessment of calibrated index (Condition B)

Equipment Combination	RDW (Relative Difference by Weight)			ICRD (Relative Difference Calibrated Index)			ICW (Weight Calibrated Index)			{(A)+(B)+(C)}×100 Revised Index
	Const. Cost (A)	Duration (B)	Envnt. Cost (C)	Const. Cost Index (A)	Duration Index (B)	Envnt. Cost Index (C)	Const. Cost Index (A)	Duration Index (B)	Envnt. Cost Index (C)	
Comb. 1	0.00	0.00	0.00	10.00	10.00	10.00	1.10	2.20	6.70	1,000
Comb. 2	–0.06	0.04	–0.05	9.94	10.04	9.95	1.09	2.21	6.66	997
Comb. 3	0.09	0.14	0.01	10.09	10.14	10.01	1.11	2.23	6.71	1,005
Comb. 4	0.20	0.07	–0.04	10.20	10.07	9.96	1.12	2.22	6.67	1,001
Comb. 5	0.18	0.00	–0.16	10.18	10.00	9.84	1.12	2.20	6.59	991
Comb. 6	0.37	0.42	–0.21	10.37	10.42	9.79	1.14	2.29	6.56	999
Comb. 7	0.25	0.00	–0.08	10.25	10.00	9.92	1.13	2.20	6.65	997
Comb. 8	0.30	0.11	–0.14	10.30	10.11	9.86	1.13	2.22	6.61	996
Comb. 9	0.06	1.47	0.01	10.06	11.47	10.01	1.11	2.52	6.71	1,034
Comb. 10	0.18	1.47	–0.04	10.18	11.47	9.96	1.12	2.52	6.67	1,032
Comb. 11	0.38	1.47	0.03	10.38	11.47	10.03	1.14	2.52	6.72	1,039
Comb. 12	0.51	1.47	–0.03	10.51	11.47	9.97	1.16	2.52	6.68	1,036
Comb. 13	0.33	1.47	–0.14	10.33	11.47	9.86	1.14	2.52	6.61	1,027
Comb. 14	0.46	1.47	–0.20	10.46	11.47	9.80	1.15	2.52	6.57	1,024
Comb. 15	0.29	1.51	–0.07	10.29	11.51	9.93	1.13	2.53	6.66	1,032
Comb. 16	0.41	1.47	–0.12	10.41	11.47	9.88	1.15	2.52	6.62	1,029

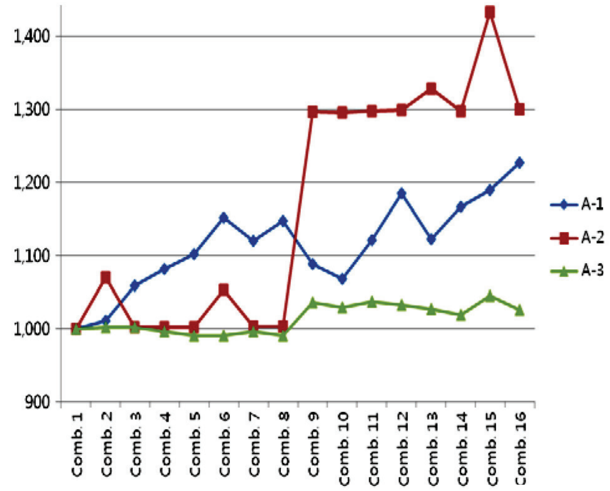

Fig. 5. Variations of revised index according to weights (Condition A)

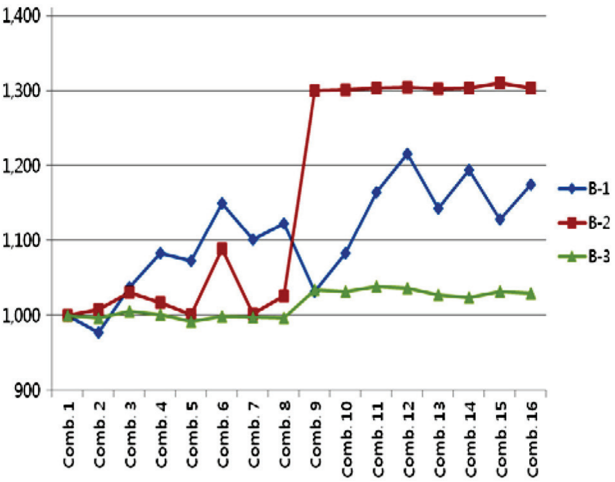

Fig. 6. Variations of revised index according to weights (Condition B)

important criteria. Though equipment combination #2 seems the most advantageous combination in the case of B-1, as seen in Figure 6, equipment combinations #1 and #5 seem the most advantageous combinations in cases of B-2 and B-3, respectively.

Conclusions

This study contributes to knowledge by adding the environmental impacts perspective to the existing literature on the selection of equipment combinations based on construction duration and costs. This study aimed at developing earthwork equipment selection method considering environmental impacts, construction costs and duration. To this end, the study has developed a discrete event simulation model for construction expenses and duration, and has utilized a method that converts environmental pollutant emissions, according to energy consumption in earthwork equipment, into environmental expenses.

In addition, this study has developed a methodology capable of selecting various equipment combinations, according to user-defined criteria, by utilizing relative difference and weight between each assessment criterion. This study found that the equipment configuration results could vary by the weight of each criterion being changed.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2011-0015361).

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