

Article

Quantitative Decision Making Model for Carbon Reduction in Road Construction Projects Using Green Technologies

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Abstract: Numerous countries have established policies for reducing greenhouse gas emissions and have suggested goals pertaining to these reductions. To reach the target reduction amounts, studies on the reduction of carbon emissions have been conducted with regard to all stages and processes in construction projects. According to a study on carbon emissions, the carbon emissions generated during the construction stage of road projects account for approximately 76 to 86% of the total carbon emissions, far exceeding the other stages, such as maintenance or demolition. Therefore, this study aims to develop a quantitative decision making model that supports the application of green technologies (GTs) to reduce carbon emissions during the construction stage of road construction projects. First, the authors selected environmental soundness, economic feasibility and constructability as the key assessment indices for evaluating 20 GTs. Second, a fuzzy set/qualitative comparative analysis (FS/QCA) was used to establish an objective decision-making model for the assessment of both the quantitative and qualitative characteristics of the key indices. To support the developed model, an expert survey was performed to assess the applicability of each GT from a practical perspective, which was verified with a case study using two additional GTs. The proposed model is expected to support practitioners in the application of suitable GTs to road projects and reduce carbon emissions, resulting in better decision making during road construction projects.

Keywords: carbon reduction; green technology; decision making; fuzzy set/Qualitative Comparative Analysis (fs/QCA); road project; construction stage

1. Introduction

1.1. Background and Purpose

In response to the increased awareness of global warming, countermeasures against greenhouse gas emissions were prepared by the United Nations Conference on Environment and Development (UNCED) at the Rio Earth Summit held in Brazil in 1992. Since then, international efforts have continued to reduce greenhouse gas emissions through the Kyoto Protocol in 1997 and the Copenhagen Accord in 2009, among other initiatives. Recently, many countries around the world have outlined action plans to reduce greenhouse gas emissions and are preparing policies that include their reduction goals. Among developed countries, examples of reduction goals by the year 2020 include 34% in the UK, 20% in the EU, 17% in the US and 15% in Japan.

Korea was ranked sixth in carbon emissions among United Nations Framework Convention on Climate Change (UNFCCC) member countries, following the US, Russia, Japan, Germany and Canada [1]. In addition, Korea's increase rate of carbon emissions over the last 20 years (*i.e.*, 1990 to 2010) was highest in the world (146%), far surpassing those of Chile (125%), Turkey (109%) and Israel (103%) [1]. Currently, Korea is classified as a "Non-Annex I" party and is thus not under any obligation to reduce greenhouse emissions. However, it is highly probable that Korea will be classified as an "Annex I" party in the near future. Accordingly, in 2009, the Korean government voluntarily set the goal of reducing greenhouse gas emissions to 30% by 2020. Based on the greenhouse gas emissions reduction goals for each section and industry set by the Korean government, the reduction goal for the construction industry was established to 7.1% [1].

According to the aforementioned statistics and data, construction companies are compelled to making efforts to reduce carbon emissions, which require the application of Green Technologies (GTs) to reduce carbon emissions during construction phases. However, most previous studies have focused on reductions in energy consumption and traffic volume control in the maintenance stage of infrastructure facilities, whereas the literature in the construction stage is still insufficient. A few studies have been conducted on GTs, but none have applied their methods in a practical setting. Therefore, in this study, the reduction of carbon emissions during the construction of a road infrastructure facility is analyzed and a decision-making model is developed to support carbon reduction decisions by providing quantitative guidelines for the application of GTs.

1.2. Scope and Method

There exist three stages in the road construction project, which are the planning (design included), construction and maintenance (operation included) stages. Each stage requires different GTs in reducing the carbon emission of the projects. However, the construction stage produces the highest carbon emission compared to the other stages. An application of the existing GTs during this stage can

also reduce the emission most effectively. Therefore, this study focuses on the reduction of carbon emissions during the construction stage of road projects. To achieve this goal, an extensive literature review was conducted using various sources and perspectives, including research articles, news reports, periodical publications, books and the accessible internet, to investigate the current status of the GTs. The decision-making model is developed through expert surveys and actual project data to establish an objective decision-making model using a fuzzy set/qualitative comparative analysis (FS/QCA) that is of both quantitative and qualitative nature. The proposed model is then verified by applying an illustrative case application.

2. Literature Review

The literature review is divided into two sections; the first section describes the carbon emission focusing on the construction field, and the second section describes the assessment indices of the GTs to be applied in the proposed model. The first section covers various topics such as different types of construction projects (*ex.* building and infrastructure) and also covers the different stages (*ex.* planning, construction and maintenance). The second section covers different perspectives of deriving the factors to assess GTs in the field of construction.

2.1. Literature on Carbon Emissions in the Construction Field

Previous studies related to carbon emissions can be classified by whether they predict or estimate the amount of emissions. According to the divided stages of a construction project, the planning stage focuses on the management of the carbon emission that will be applied in the following stage that predicts and estimates the amount [2,3]. The construction stage focuses on the calculation of the actual amount of the emission to compare between the different technologies applied [4–6]. On the other hand, the maintenance stage covers a long-term management method that impacts the carbon emissions over the usage time of the facility [7–9]. Some studies have conducted an assessment of carbon emissions that covers the whole project life-cycle [10–12].

The assessment of the construction process revealed that different types of facilities had different carbon emission characteristics. The carbon emissions throughout the construction process of buildings and transportation (e.g., road project) were compared, and here the results of the carbon emissions at the maintenance (including operation) stage accounted for 56 to 88% of all carbon emissions. This emission of carbon was, however, largely caused by external usage, such as building energy usage and traffic based fuel usage, that corresponded to the areas. Through a further analysis that exempted the external usages, the construction stage of buildings and transportation contributed to the emission of carbon with up to 83% and 76%, respectively [12–14].

Different carbon emission characteristics were also influenced in respect to material types used in the construction stage. For example, pavement materials for road projects used concrete or asphalt or even a combination of both materials [13,15]. Pavements made of concrete and asphalt showed 52% and 86% of carbon emission in the construction stage, respectively. According to this result, asphalt pavement emitted five times more carbon than concrete pavement [15]. Therefore, it is necessary to reduce the carbon emission, specifically during the construction stages of the facility, and to select the appropriate material to achieve the reduction goals at the construction industry level.

2.2. Identification of Factors for the Assessment of Green Technologies

In this study, a GT is defined as a construction method that reduces carbon emissions. GTs are being developed and practically used to support the target goal. According to different types of work, various GTs have been applied to reduce carbon emission. Typically, efforts to reduce emissions during the construction stage involve the efficient operation of heavy equipment usage at the actual construction sites. Since construction materials such as cement, steel materials and aggregates are processed as products, carbon is emitted during these manufacturing procedures; thus, to reduce carbon emissions during construction, it is also necessary to consider the carbon emissions from the production of these construction materials [14,16]. Accordingly, we divided the types of GTs into work type for the input of fuels for the construction equipment and materials in this study.

During the decision-making process for applying GTs, decision-makers are to sufficiently consider each available GT list including the expected reduction amount by the application of the technology. Although the rate of carbon emission reduction is an important factor to consider, other potential effects are considered, such as the increased costs, extended duration of construction time, as well as the impacts given by applying such technology. However, previous studies on examining the factors that consider the selection of a GT during the construction stage are still scarce. Earlier research is limited to merely analyzing the selection of the typical construction method while this research aims to further identify the appropriate GTs to be considered.

Previous studies on the selection of construction methods attempted to compare the life-cycle costs of individual construction methods [17,18]. In a wider perspective, economic feasibility and other factors, such as constructability, maintenance convenience and aesthetic quality were also considered using multi-criteria decision-making processes [19,20]. Furthermore, the carbon emission factors (*i.e.*, environmental soundness) when evaluating the suitability of construction methods are also examined [21,22].

The assessment indices for selecting construction methods are summarized as appropriateness, economic feasibility, constructability, environmental soundness and other assessment factors pertaining to the applied construction method. The authors considered these conventional assessment indices in order to measure the application of a GT. Therefore, to select as an appropriate GT to be applied as the construction method, the three primary assessment factors must be satisfied, which are environmental soundness, economic feasibility and constructability. Since the economic feasibility is self-explanatory, extensive literature can be found that defines constructability and environmental soundness. Constructability is defined as the ease of application of the construction method on-site. The authors have subdivided the constructability into six detailed qualitative components, *i.e.*, difficulty of construction, degree of construction experience, availability of construction equipment, availability of construction materials, availability of skillful participants and likelihood of accidents. Specifically, qualitative assessment factors are considered to assess the constructability whereas environmental soundness and economic feasibility are assessed quantitatively. Environmental soundness is a topic that is widely used in the field of construction, which has different definitions according to the scope of each research project [21,23]. This study defines environmental soundness as factors that minimize the effect of the nature that is created during the construction stage. Examples of factors that affect the nature are dust, CO₂, SO_x, NO_x, *etc.* These by-products cause air and water pollution, global warming, as well as human diseases [15,24]. However, as considering all the environmental factors and their

impacts will be the focus of our future studies, this research focuses on the carbon emission where the quantitative perspective of the GT is analyzed to derive the actual reduction of CO₂ emission.

3. Research Methods

In the present study, environmental soundness, economic feasibility and constructability were selected as the three primary assessment factors. Therefore, an integrated analysis method of quantitative and qualitative data is essential for analyzing both dimensions of assessment factors.

3.1. Fuzzy Set/Qualitative Comparative Analysis (FS/QCA)

Ragin (1994) noted that a qualitative method allows for detailed case studies with results that may not be easily generalized, while a quantitative method allows for a generalization but at the expense of the feasibility of conducting detailed case studies. To address this tradeoff, fuzzy set/qualitative comparative analysis (FS/QCA) was developed. FS/QCA was suggested as a means of overcoming the limitation of a small number of cases by embracing the basic assumption pertaining to qualitative case studies in the social sciences: that the cause and effect relationships between the combined factors of various cause conditions and result conditions should be investigated by analyzing the context [25]. In the field of social sciences, when there is a small or medium number of cases, FS/QCA enables the identification of diversity that may not be recognized by a qualitative study method, even with a very small number of cases. At the same time, this method considers the qualitative nature of cases, which is neglected in a quantitative study method that is dependent on case incidence factors. In addition, many studies have introduced the fuzzy theory concept for the joint analysis of quantitative data and qualitative data. Originally developed by Professor Lotfi Zadeh, fuzzy theory is used to systematically solve problems characterized by uncertainty and inaccuracy due to the ambiguity of language.

The traditional qualitative comparative analysis (QCA) is a crisp set form of QCA, providing only binary results (*i.e.*, 1 or 0) based on Boolean algebra. Since the values are binary, 1 represents complete membership and 0 represents complete non-membership. In contrast, fuzzy set QCA considers cause conditions and result conditions as a single set and further shows how much of each condition is included in the set. Because the FS/QCA integrates a qualitative method and a quantitative method, raw scores should be modified as fuzzy scores. A fuzzy score represents the extent to which a phenomenon belongs to the concept condition. Generally, a three point fuzzy set that is represented as 0, 0.5 and 1 is used as the set where 0.5 is neither a member of both ends. However, depending on the research objectives, four point, six point, or even continuous fuzzy sets can be employed which are represented as 0, 0.33, 0.66, 1, or 0, 0.2, 0.4, 0.6, 0.8, 1, respectively [26]. Continuous fuzzy sets on the other hand can be divided into any equidistant intervals between 0 and 1.

The analysis of this study is conducted using 22 GTs selected from the literature review, therefore the number of cases is insufficient to apply statistical analysis (*i.e.*, regression analysis) for quantitative analysis. Conversely, when the analysis is performed through case study (qualitative method), the result is focused on a specific case that is used to analyze the research that cannot be applied to a general phenomenon [27]. Therefore, the qualitative method is not suitable for deriving general conditions for determining whether a particular GT is appropriate for a given condition. It is a method capable of dealing with intermediate numbers of samples, therefore this study employed the FS/QCA

method for the analytical method to perform both quantitative and qualitative analyses. To further enhance this methodology, Ragin, Drass and Davey developed a FS/QCA 2.0 software program [26].

3.2. Questionnaire Survey

To develop a decision-making model when applying a GT to reduce carbon emissions in the construction stage, a questionnaire survey was conducted with industry experts who acted as key decision-makers from the planning to construction stage. The questionnaire was organized into three parts.

Part 1 included questions for assessing the weights of the three assessment factors: environmental soundness, economic feasibility and constructability. In Part 2, the detailed sub-factors under the category of the constructability, that is qualitative, were assessed in full detail. The six detailed sub-factors selected on the basis of the previous studies were (1) difficulty of construction; (2) degree of construction experience; (3) availability of construction equipment; (4) availability of construction materials; (5) availability of skillful participants; (6) possibility of accidents. The respondents were asked to assess each of the factors with respect to the applicability of the GTs.

Part 3 provided prior information on each of the assessment factors of a given individual GT. This information collected through the literature review was used for the assessment of constructability and for the final decision-making process of whether those GTs might be adopted to reduce carbon emissions. The information on the rate of carbon emission reduction and any increases in construction costs and construction duration were also collected by reviewing the extensive previous studies including journal articles, press releases and periodical publications. Based on these three parts of contents, a total of 75 questionnaires were distributed, of which 39 questionnaires were returned, which corresponds to a 52% response rate. Among the 39 returned questionnaires, 15 had a low reliability with many missing values; thus, the remaining 24 questionnaires were used for further data analysis. In order to support the reliability of the questionnaire analysis research, a response rate higher than 23% is considered reportable in the field of construction [28]. Furthermore, a sample size larger than 20 responses is also valid to obtain reasonable conclusions [29].

4. Quantitative Decision Making Model for Selecting a GT

4.1. Proposition of Framework

The proposed model aims to develop a quantitative decision-making model, which is composed of five steps (refer to Figure 1). As the figure shows, this research focuses on the construction stage of an infrastructure project. Step 1 is the selection of the infrastructure project type. The major work types and activities responsible for carbon emissions and the applicable GTs are dependent on the types of infrastructure facilities. This study conducts a specific case analysis using a road facility. In Step 2, the amounts of carbon emissions for each work activity during the construction stage are estimated, compared and analyzed. In addition, based on the estimated carbon emissions, the key work item that contributes the most to carbon emissions is determined. Step 3 involves the selection of a green technology applicable to the given work type and activity, which is obtainable by investigating the GT database. Since new GTs are constantly being developed and companies are not prone to open their data due to concerns of intellectual property [5], the database of the present study is established on the

basis of a review of previous studies and other accessible information available from several construction companies. In addition, when a new technology applicable to the key work item is not found in the current database, an existing construction method is selected instead by comparing the carbon emissions of conventional construction methods. In Step 4, individual GTs are assessed based on the three assessment parameters (*i.e.*, environmental soundness, economic feasibility and constructability) using the FS/QCA method. Step 5 summarizes the analytical results from the previous steps and suggests an appropriate GT for the user's decision-making process.

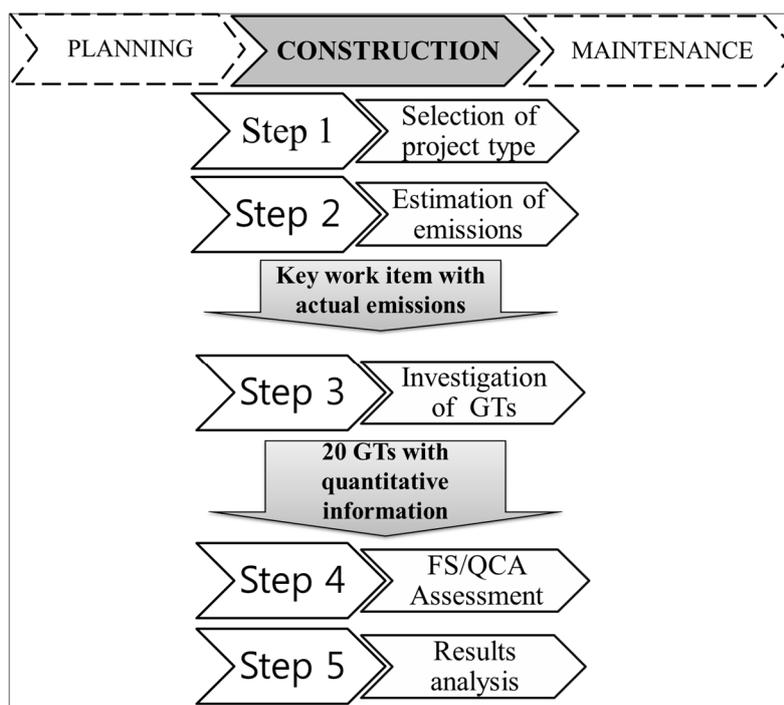


Figure 1. Framework of decision-making model.

4.2. Selections of Project Type and Estimation of Emissions

This analysis focuses on road construction projects, which represent the most prevalent infrastructure facility. When applying a GT to reduce carbon emissions during the construction, the work type with the greatest effect on construction cost and carbon emissions should be identified in order to apply the technology. To this end, the road construction project was further divided into detailed work types, and the ratios of the input expense, input materials and input fuels for each of the detailed work types were subsequently compared. First, the input expense for each work type was calculated with reference to the Bill of Quantity (BOQ). As numerous equipment and materials are consumed in the construction of a road project, it is not realistic to analyze all of the equipment items and materials. To identify the key work types, the analysis was conducted with the most frequently used equipment components and the materials that are typically required in large-scale road construction projects. Given that information pertaining to the actual usage of a piece of equipment may not be found in the construction account or other data, a standard estimate of a road construction project was used to calculate the actual usage time based on the information on each piece of equipment with regard to the construction supply, equipment efficiency and amount of processing per

hour [7]. Input materials were estimated with reference to a material computation document based on a total of 202 as-built road samples. Table 1 shows the analyzed data.

Table 1. Input analysis of road construction projects.

Work Type	Input Expense	Input Material			Input Fuel
		Concrete	Asphalt Concrete	Reinforcing Steel Bars	
1. Earth Work	26%	0%	0%	0%	54%
2. Slope stabilization work	3%	0%	0%	0%	2%
3. Drainage work	14%	56%	0%	49%	1%
4. Pavement work	38%	19%	98%	0%	43%
5. Traffic safety work	6%	2%	0%	2%	0%
6. Subsidiary work	13%	23%	2%	49%	1%
	100%	100%	100%	100%	100%

As shown in Table 1, the input expense for each work type is highest for pavement work, followed by earth work, drainage work, subsidiary work, traffic safety work and slope stabilization work. With respect to the input materials, the concrete input is highest for drainage work, followed by subsidiary work, pavement work and traffic safety work. For asphalt-concrete input, the highest is pavement work, followed by subsidiary work. For reinforcing steel bar input, the highest is subsidiary work, followed by drainage work and traffic safety work. The input fuel associated with the utilization of equipment items is highest for earth work, followed by pavement work and other work types. The results show that earth work and pavement work are the key work types in terms of input expense and fuel consumption. However, it is unreasonable to select the key work types based only on the ratio of input materials. The carbon emissions caused by the use of each material type should be compared to the carbon emissions caused by each work type.

Table 2. Carbon emission analysis by materials.

	Drainage Work	Pavement Work	Traffic Safety Work	Subsidiary Work	Total
Asphalt-concrete	0.00%	93.92%	0.00%	0.00%	93.62%
Concrete	3.41%	1.16%	0.14%	1.37%	6.08%
Reinforcing steel bars	0.00078%	0.00000%	0.00003%	0.00078%	0.00159%

In general, when estimating greenhouse gas emissions, the total emissions can be easily calculated by multiplying the amount of used materials by the carbon emissions coefficients provided by the Intergovernmental Panel on Climate Change (IPCC) [7,30]. As shown in Table 2, 94% of the carbon emissions produced by the use of the materials is emitted from the use of asphalt-concrete and 100% of the asphalt-concrete input is used for pavement work. Therefore, the key work types selected after considering the input expenses and the carbon emissions caused by the use of the equipment items and materials are found for earth work (from Table 1) and pavement work (from Tables 1 and 2).

4.3. Investigation of the GTs

The GTs collected from the previous literature review can be applied to earth work, pavement work and structural work. Among the listed GTs, applicable technologies are determined based on the

assessment factors in the following step. Since industry practitioners who select GTs are likely to rely on subjective opinions, the analysis of the assessment criteria through a questionnaire survey identifies the pattern of decision-making. For this purpose, we performed a survey on the decision-making activities by 24 industry experts. The collected questionnaires were then analyzed through FS/QCA to develop a decision-making model.

4.4. FS/QCA Assessment

Within the questionnaire survey, prior-information pertaining to the environmental soundness and economic feasibility of the 20 GTs collected through the analysis of the previous studies is summarized. Information that is not available in the previous studies was also collected from press releases and individual expert consultations. Table 3 shows the 20 GTs used in the survey and includes the data on the carbon emissions, construction cost and construction duration caused by applying individual GTs.

In contrast to environmental soundness and economic feasibility factors, constructability is a qualitative factor. Therefore, expert opinions on constructability were also quantified in the survey. Expert opinions on constructability with respect to individual GTs were categorized as difficult, moderate, or easy. These results were converted into scores, which were summed to obtain the final raw scores for constructability by triangular membership function as (0, 1, 3), (3, 5, 7) and (7, 9, 10), respectively. Although there are many types of membership functions representing linguistic variables, this study employed a triangular membership function to apply the linguistic scale proposed by Chen *et al.* [21].

Six detailed assessment factors of constructability were assessed using the same method. The survey was performed using the 20 GTs to collect expert opinions on constructability. The survey results were summarized by scoring the linguistic scales. Table 4 shows the raw scores for environmental soundness, economic feasibility and constructability. For environmental soundness and economic feasibility (construction cost, construction duration) 100% is substituted with 1, whereas the increments of the indices are calculated (*i.e.*, GT1's indices shows 22% decrease, 20% decrease, 10% decrease, the values are substituted as 0.78, 0.8, and 0.9 accordingly) and the six indices for constructability are also substituted accordingly. The last column of Table 4 also shows the raw scores for the GT adoption rates of experts obtained from the survey.

To perform the FS/QCA with respect to constructability, which is a qualitative index, the raw scores of the six established cause conditions having constructability were converted into fuzzy scores. Although each GT had its own score of constructability based on the survey, it was assumed that the same type of GTs had the same score of constructability, *i.e.*, 0.45 in GT 3 and 4. Table 5 shows the results of the constructability analysis and the fuzzy scores of the cause conditions and the result conditions of a given GTs.

Table 3. Analysis results of green technologies (GT).

GT Item	Name of GT	Applied Work Type	Environmental Soundness (Carbon Emissions)	Economic Feasibility	
				Construction Cost	Construction Duration
GT1	Machine Guidance	Earth Work	22% decrease	20% decrease	10% increase
GT2	Fleet Management	Earth Work	20% decrease	10% increase	-
	Optimum Combination of Civil				
GT3	Engineering Instrument without Delay	Earth Work	8% decrease	20% decrease	-
	Optimum Combination of Civil				
GT4	Engineering Instrument with Delay	Earth Work	15% decrease	15% increase	5% increase
GT5	Increase Truck Fleet Size	Earth Work	48% decrease	-	29% decrease
GT6	Reduce Excavator Fleet Size	Earth Work	4% decrease	18% increase	18% increase
GT7	Change of the Dumping Site	Earth Work	5% decrease	10% increase	19% increase
GT8	Oil-Free Air Compressor	Machine	10% decrease	5% increase	-
GT9	Inverter-Type Energy-Saving Variable-Speed Drive Technology	Machine	42% decrease	10% increase	-
GT10	GIS Analysis-based Optimum Positioning of Spoil-Bank	Earth Work	20% decrease	5% decrease	5% increase
	Design Technique for Economic Civil				
GT11	Engineering Movement and Transport Route	Earth Work	20% decrease	10% increase	10% decrease
GT12	Recycling of Aggregates in Pavement works	Pavement Works	10% decrease	10% decrease	10% increase
GT13	10% Recycling of Aggregates	Pavement and Structural Works	12% decrease	5% decrease	5% decrease
GT14	20% Recycling of Aggregates	Pavement and Structural Works	15% decrease	8% decrease	5% decrease
GT15	30% Recycling of Aggregates	Pavement and Structural Works	18% decrease	10% decrease	5% decrease
GT16	Low-Carbon-Emission Concrete Curing	Structural Works	55% decrease	15% increase	10% decrease
GT17	Low-Carbon-Emission Concrete (General Type)	Pavement and Structural Works	20% decrease	5% increase	-
GT18	Low-Carbon-Emission Concrete (Hot-Weather Type)	Pavement and Structural Works	40% decrease	5% increase	-
GT19	Low-Carbon-Emission Concrete (Mass Type)	Pavement and Structural Works	60% decrease	10% increase	-
GT20	Low-Carbon-Emission Medium-Temperature Asphalt Pavement	Pavement Works	32% decrease	10% increase	20% decrease

Table 4. Average raw score of cause and result conditions.

GT	Cause Conditions			Result Conditions	
	Environmental Soundness (Carbon Emissions)	Economic Feasibility		Constructability	Final Decision (Ratio of GT Adoption)
		Construction Cost	Construction Duration		
GT1	0.78	1.20	1.10	6.67	0.38
GT2	0.80	1.10	1.00	4.83	0.42
GT3	0.92	1.20	1.00	4.17	0.50
GT4	0.95	1.15	1.05	4.13	0.39
GT5	0.52	1.00	0.81	3.67	0.79
GT6	0.96	1.18	1.18	4.00	0.17
GT7	0.95	1.10	1.19	3.17	0.25
GT8	0.90	1.05	1.00	4.83	0.21
GT9	0.58	1.10	1.00	6.17	0.33
GT10	0.80	1.05	1.05	4.83	0.50
GT11	0.80	1.10	0.90	4.33	0.46
GT12	0.90	0.90	1.10	3.33	0.75
GT13	0.88	0.95	0.95	4.00	0.75
GT14	0.85	0.92	0.95	4.17	0.67
GT15	0.82	0.90	0.95	4.13	0.58
GT16	0.45	1.15	0.90	5.50	0.54
GT17	0.80	1.05	1.00	5.00	0.46
GT18	0.60	1.05	1.00	5.17	0.58
GT19	0.40	1.10	1.00	5.00	0.50
GT20	0.68	1.10	0.80	4.83	0.63

Table 5. Results of fuzzy score analysis.

Carbon Emissions Reduction Technology	Cause Conditions			Result Conditions	
	Environmental Soundness (Carbon Emissions)	Economic Feasibility		Constructability	Final Decision (Ratio of GT Adoption)
		Construction Cost	Construction Duration		
GT1	0.49	0.55	0.55	0.73	0.38
GT2	0.50	0.50	0.50	0.53	0.42
GT3	0.58	0.55	0.50	0.45	0.50
GT4	0.59	0.52	0.53	0.45	0.39
GT5	0.33	0.45	0.41	0.40	0.79
GT6	0.60	0.54	0.59	0.44	0.17
GT7	0.59	0.50	0.60	0.32	0.25
GT8	0.56	0.48	0.50	0.53	0.21
GT9	0.36	0.50	0.50	0.67	0.33
GT10	0.50	0.48	0.53	0.53	0.50

Table 5. Cont.

Carbon Emissions Reduction Technology	Cause Conditions				Result Conditions
	Environmental Soundness (Carbon Emissions)	Economic Feasibility		Constructability	Final Decision (Ratio of GT Adoption)
		Construction Cost	Construction Duration		
GT11	0.50	0.50	0.45	0.47	0.46
GT12	0.56	0.41	0.55	0.36	0.75
GT13	0.55	0.43	0.48	0.44	0.75
GT14	0.53	0.42	0.48	0.45	0.67
GT15	0.51	0.41	0.48	0.45	0.58
GT16	0.28	0.52	0.45	0.60	0.54
GT17	0.50	0.48	0.50	0.55	0.46
GT18	0.38	0.48	0.50	0.56	0.58
GT19	0.25	0.50	0.50	0.55	0.50
GT20	0.43	0.50	0.40	0.53	0.63

4.5. Analysis and Results

4.5.1. Analysis of Truth Table

After converting the raw scores to fuzzy scores, truth table analysis is performed to assess a combination between the cause and result conditions. In the analysis, 2 to the power of n combinations can be counted for n number of cause conditions. First, a truth table analysis to was performed to assess the constructability with respect to the detailed six constructability assessment factors (*i.e.*, cause conditions) and total quality of constructability (*i.e.*, result conditions).

The scores of the cause conditions (X) and the result conditions (Y) measured by fuzzy scores are compared with each other. A necessary condition is established when the score of a cause condition is greater than the result condition ($Y < X$), while a sufficient condition is established when the score of a cause condition is less than the result condition ($X < Y$). In FS/QCA, significance is evaluated for the consistency of the cases for the verified conditions. Consistency represents how stable the results are for the same conditions or combination of conditions. The range of consistency is between 0 and 1, and consistency is calculated using the following equation:

$$\text{Consistency}(Y < X) = \frac{\sum \min(X, Y)}{\sum Y} \quad (1)$$

In Equation (1), X denotes a fuzzy score of a cause condition combination, and Y denotes a fuzzy score of a result condition combination. Ragin stated that 0.75 is considered as a low level of consistency [26]. In this study, the consistency threshold is set at 0.85.

Coverage refers to the ratio of actual cases that can be explained by the derived model. For example, the coverage of the model derived by the analysis was 0.940239. This outcome indicates that the model can explain 94% of the cause condition combinations pertaining to constructability. Coverage is calculated with the following Equation (2), where X denotes a fuzzy score of a cause condition combination and Y denotes a fuzzy score of a result condition combination:

$$\text{Coverage} = \frac{\sum \min(X, Y)}{\sum Y} \quad (2)$$

Next, the cause conditions and the result conditions for decisions on GTs were analyzed. The consistency reference score for this analysis was also set at 0.85 at the higher level. Table 6 shows the validation results of the necessary conditions for decisions on GTs.

Table 6. Validation result of constructability with green technologies.

Detailed Factors	Cause Condition	Consistency	Coverage	Cause Condition Negation	Consistency	Coverage
Environmental soundness	e	0.822732	0.800203	~e	0.835735	0.882353
Economic feasibility (Construction cost)	f	0.840535	0.828600	~f	0.864786	0.901623
Economic feasibility (Construction duration)	d	0.831000	0.842799	~d	0.853561	0.863083
Constructability	c	0.821713	0.836714	~c	0.861446	0.870183

In this analysis, three cause conditions had a level beyond the threshold of consistency: economic feasibility (construction cost), economic feasibility (construction duration) and constructability. Therefore, the total number of cause condition combinations was eight. According to Ragin [26], one or two is generally set as a case number threshold in a truth table analysis. In this analysis, cause condition combinations with zero cases were excluded, whereas those with one and two cases were included. In this analysis, a result condition score of 1 was given for those consistency scores that resulted in 0.85 or higher (Table 7).

Table 7. Truth table with result condition (decision making)—applying GT.

Combination Number	Economic Feasibility (Construction Cost)	Economic Feasibility (Construction Period)	Constructability	Number of Corresponding Case	Decision-Making	Consistency
1	0	0	1	3	1	0.877706
2	1	1	1	2	0	0.840045
3	0	1	0	2	1	0.895787
4	1	1	0	1	0	0.840460
5	1	0	0	1	1	0.892734
6	1	0	1	0	0	-
7	0	1	1	0	0	-
8	0	0	0	0	0	-

The result of the truth table analysis shows five cause condition combinations that correspond to the cases. The same rule as mentioned above was applied to the constructability score. A total of three cause condition combinations showed consistency of 0.85 or higher. Two cause condition combinations had consistencies less than 0.85, and the result condition score of 0 was accordingly

given to these two combinations. The sufficient conditions were verified to derive the cause condition combinations shown in Table 8.

Table 8. Sufficient condition of decision making—applying GT.

Item	Derived Model	Coverage	Consistency	Corresponding Technology
Model 1	~ Constructability ~ Construction cost *	0.809331	0.874936	GT5, GT12
Model 2	~ Construction duration * Constructability	0.822515	0.877706	GT13

Note: Constructability (High level of difficulty)—Constructability (Low level of difficulty)—Construction cost (Decrease the cost)—Construction duration (Shorten the duration), * (Simultaneously consider the next factors).

The coverage of Model 1 derived by the analysis was 0.809331. This finding indicates that Model 1 can explain decision-making at a rate of approximately 81%. The coverage of Model 2 was 0.822515, indicating that Model 2 has an explanation power of approximately 82%.

Expert opinions pertaining to the two previously derived models were analyzed. Model 1 implies that when the application of a GT reduces carbon emissions, decision-makers preferentially first consider constructability. When a type of GT is convenient to apply, which indicates that the technology has a low level of construction difficulty, the probability of GT application increases, even if the construction cost and duration may increase. Conversely, in the case of Model 2, when a GT has a low constructability level (*i.e.*, when the technology has a difficulty level), the probability of the GT being applied can be increased only if the technology decreases the construction costs and shortens the construction duration. The two derived models indicate that the decision-making criteria concerning the application of a GT include not only the rate of carbon emission reduction but also the constructability of a given GT. Moreover, economic factors, such as construction expense and the length of the construction period should be strongly considered.

Next, an additional analysis was performed with respect to cases in which no decision was made with regard to the application of a GT. The decision-making variables, which were the result conditions, were included in the complementary set (*i.e.*, reject the GT) to analyze the cause conditions.

As shown in the previous analysis, the total number of cause condition combinations from three assessment factors was eight. Because the lowest consistency score was 0.872910, the consistency reference score was set to 0.9. When the consistency score was 0.9 or higher, the case was considered having a result condition (thus being assigned a score of 1). Sufficient conditions were verified to derive the cause condition combinations shown in Table 9.

Similarly to the previous analysis, coverage refers to the ratio of actual cases that can be explained by the derived models. The coverage of Model 3 derived by the analysis was 0.851085, indicating that Model 3 can predict decision-making at a rate of approximately 85%. In addition, the coverage of Model 4 was 0.821499, indicating that Model 4 has an explanatory power of approximately 82%.

The expert opinions on the two derived models were analyzed. Model 3 emphasized that when applying a GT, decision-makers preferentially consider an increase in construction expenses and construction duration. When the application of a GT increases construction expenses and duration, imposing an economic burden, the decision-makers are reluctant to apply the GT. In the case of

Model 4, the result shows that when the application of a GT with a high construction difficulty level increases the construction duration, the probability of applying the GT decreases. Considering the result of Model 2 for the GT application, the decision is made not to apply a GT with a high construction difficulty level if the construction duration is likely to be extended, whereas the opposite is true when both the construction cost and the construction period are to be reduced.

Table 9. Sufficient condition of decision-making—do not apply to GT.

Item	Derived Model	Coverage	Consistency	Corresponding Technology
Model 3	Construction cost * Construction duration	0.851085	0.919063	GT1
Model 4	Construction duration * Constructability	0.821499	0.910382	GT6

Note: Constructability (High level of difficulty), Construction cost (Increase the cost), Construction duration (Delay the duration), * (Simultaneously consider the next factors).

4.5.2. Analysis of a Negative Case

Negative case refers to a case that does not give a result condition despite a high cause condition score satisfying a necessary condition. Negative cases are better explained by using other necessary conditions. Alternatively, when the negative cases are not explained by the selected necessary condition, other cause conditions should be considered. These negative cases provide the basis for the case study.

Negative cases were selected by applying a 4-point fuzzy set [26]. The cases in which the cause conditions verified as necessary conditions had a fuzzy score of 0.66 or higher, indicated that the condition was mostly included in the set, but not completely. When the result condition (*i.e.*, decision-making probability) had a fuzzy score of 0.33 or lower, it indicated that the conditions mostly, but not completely, excluded from the set were selected as negative cases. Table 10 shows the GTs that were selected as negative cases with reference to the criteria.

Table 10. Results of fuzzy score analysis (Negative case).

Carbon Emissions Reduction Technology	Cause Conditions			Result Conditions	
	Environmental Soundness (Carbon Emission)	Economic Feasibility		Final Decision (Ratio of GT Adoption)	
		Construction Cost	Construction Duration		Constructability
GT7	0.59	0.50	0.57	0.32	0.25
GT9	0.36	0.50	0.49	0.67	0.33

Two GTs, GT7 (a change of the dumping site) and GT9 (inverter-type energy-saving variable-speed drive technology), were selected as negative cases. Case GT7 had a constructability fuzzy score of 0.32, which was lower than the negative case selection reference score of 0.33, and thus satisfied the criteria of Model 1. However, the decision-making fuzzy score (percent of GT adoption) was 0.25, which was lower than the negative case selection reference score of 0.33. This GT enables the

positioning of a dumping site closer to a work site such that the hauling time of dump trucks can be reduced and the efficiency of excavators can be increased [31]. A review of the expert opinions with regard to the analysis of this technology showed that a simulation of the transport distance and the number of movements can be easily estimated depending on the position of the dump site using various simulation tools, such as Extend program and WebCyclone. However, the location of a dumping site is usually determined at the design stage regardless of actual on-site circumstances. Therefore, it was found that applying this technology during construction was very uncommon. Hence, although the constructability of a given technology was appropriate for Model 1, the technology was selected as a negative case because the actual probability of adopting a given technology was very low.

Case GT9 showed a constructability fuzzy score of 0.67, which was applied to Model 2 and Model 4. However, the decision-making probability fuzzy score (percent of GT adoption) was 0.33, which was equal to the reference score of a negative case. This GT allows for the optimum operation of a motor through the use of an inverter-type high-efficiency motor with appropriate control technology to increase efficiency. In the negative case of GT9, the fuzzy scores pertaining to the availability of construction equipment and the availability of construction materials were higher than the average fuzzy score, as the installation of the high-efficiency inverter as a GT was considered difficult.

5. Validation of Proposed Decision-Making Model

5.1. Collection and Analysis of Additional Cases

To verify the analytical results and the four derived models presented in the previous sections, two additional GTs were added and applied to the same models. Since the existing 20 GTs were used as training data for the analysis, the validation process of using the same GTs are not justifiable. The two additional GTs are shown in Table 11. GT21 is a technology for recycling waste concrete generated at a deconstruction site or using the waste concrete as a simple landfill material. GT22 is a technology for decreasing the viscosity of asphalt to improve the coating production efficiency with aggregates at a low temperature.

Table 11. Analysis results of green technologies (Additional).

Item	GT	Applied Work Type	Environmental	Economic Feasibility	
			Soundness (Carbon Emissions)	Construction Cost	Construction Duration
GT21	On-the-Spot Recycling of Waste Concrete	Pavement and Structural Works	50% decreased	20% decrease	20% increase
GT22	Low-Carbon-Emissions Medium-Temperature Asphalt Pavement	Pavement Works	35% decreased	10% increase	5% decrease

A questionnaire survey was performed by the same group of 24 experts for the assessment of constructability. The result showed that the raw score of GT21 was 2.9 and that of GT22 was 5.

5.2. Decision-Making with Proposed Four Models

The fuzzy scores in Table 12 were analyzed, and the results showed that the constructability fuzzy score of GT21 was 0.32, indicating that the technology can be assessed by Model 1. This model shows

that the GT with a low level of difficulty (0.32) is preferentially adopted in projects. According to the result of the expert questionnaire survey, the probability of applying GT21 (on-the-spot recycling of waste concrete) was 67%. Conversely, the constructability fuzzy score of GT22 was 0.55 (higher level of difficulty than GT 21), indicating that this technology is inappropriate for Model 1. Economic factors were thus more frequently considered for application of GT22 to Model 2, which confirmed that GT22 (low-carbon-emissions medium-temperature asphalt pavement) is partially inappropriate for Model 2. Thus, additional consideration such as the possibility of an acceptance level at the cost and duration variances is required for the application of GT22. The expert questionnaire survey results also revealed that the probability of GT22 application was only 45%. Therefore, based on the comparison of the proposed model result and the actual decisions made by the practitioners, similarities were found in both.

Table 12. Results of fuzzy score analysis (Additional GT).

GT	Cause Conditions				Final Decision	
	Environmental Soundness (Carbon Emissions)	Decision-Making		Constructability	Fitting with Proposed Model	Ratio of GT Adoption from Survey
		Construction Cost	Construction Duration			
GT21	0.32	0.36	0.59	0.32	O (Model 1)	67%
GT22	0.41	0.50	0.51	0.55	X	45%

6. Conclusions

Recently, international efforts have been made to reduce carbon emissions, leading to the development of GTs and further research into their application in various areas. In the construction industry, the carbon emissions generated during the construction stage of an infrastructure facility are significantly greater than those generated during maintenance or deconstruction. Therefore, in this study, the authors developed a decision-making model that supports the decision of the application of a GT that reduces carbon emissions. In addition, the practical applicability of the models was tested by additional case studies.

In this study, the need to reduce carbon emissions during construction was verified through previous literature reviews. Next, information on GTs was collected from previous studies and various report materials to establish a database of the quantitative factors, which included environmental soundness and economic feasibility. In addition, in order to assess constructability as a qualitative factor analysis, expert interviews and a questionnaire survey were performed. Four models were proposed on the basis of the present study using Fuzzy set/Qualitative Comparative Analysis (fs/QCA). In order to test the appropriateness of these four models, two additional GTs were analyzed for the applicability. The models proposed provide directions for the development of new GTs and support the decision to apply GTs on actual construction sites.

The contribution of this research is firstly to quantify the experts' decision making process and to investigate the relationship between cause and result condition that are merged into the developed model. Since the traditional decisions are made intuitively without any reliable information, the proposed model can minimize personal biases and also suggest an appropriate GT that can be applied

to a given project. Secondly, by using the three key indices, both quantitative and qualitative analyses of decision-making are developed to support the experts' decision-making. Application of GT was mostly dependent on simple life-cycle cost analysis (LCC) analysis; this research presents a variety of perspectives in the same decision process. Thirdly, the proposed model presents a guideline for practitioners as a reference to the application of appropriate GT for future projects. In the current practice, both the assessment guideline and the prioritization method for the application of GT are insufficient. This study is significant in that the FS/QCA methodology, which is usually applied in social sciences, can be effectively employed to the field of construction. With these contributions, the burden of decision-making for the practitioners can also be reduced *in situations* when the analysis of negative cases reflects the real life phenomenon of decision-making.

The proposed models are, to some extent, limited because qualitative assessment using linguistic variables is inherently dependent on the experience of the experts, which requires accurate assessments of the experts to improve the reliability of the results. This study is also limited in that the consistency thresholds of FS/QCA are not clearly defined. In future studies, consideration of the various cause conditions for environmental soundness mentioned above (e.g., SO_x, NO_x, dust, *etc.*) are to be included to construct more detailed models.

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Author Contributions

All authors read and approved the final manuscript. Woosik Jang wrote and revised the manuscript and participated in designing the study. Hyun-woo You designed the study, interpreted the data and participated in writing the manuscript. Seung Heon Han provided directed the study and revised the manuscript's final version.

Conflicts of Interest

The authors declare no conflict of interest.

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