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Study on an Integrated LCA-LCC Model for Assessment of Highway Engineering Technical Schemes

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Abstract: This paper proposes an integrated life cycle assessment-life cycle cost (LCA-LCC) model of environmental and economic factors for highway engineering technical schemes to problems such as the limitations of single-dimensional assessment, their narrow scope, the difficulty in tracing sources, and the conflicts of various dimensions in existing integrated assessment methods. The latest documents issued by the Ministry of Ecology and Environment and the Ministry of Transport of China used as an integrated assessment database. Air pollution, water pollution, solid waste pollution, noise pollution, energy consumption, pre-project cost, project construction cost, project operation cost, and post-project cost were used to construct the integrated assessment index system of environmental and economic factors. An improved entropy method was adopted in the LCA-LCC model to overcome the problems of ambiguous results of the previous entropy due to too few assessment schemes, the inoperability of the method when it encounters a negative value or zero value, and unbalanced multi-angle assessments. This model was applied to the assessment of two asphalt pavement maintenance schemes of Highway US280 in Alabama and two improvement schemes of high liquid limit soil subgrade of Highway G360 in Hainan. The results show that the LCA-LCC model overcomes the limitations and imbalances of a single LCA or LCC. The gravel improved scheme and the cold recycling scheme were identified through quantitative assessment as more sustainable. This paper can provide a reference for the comprehensive quantitative assessment of environmental and economic benefits of highway engineering technical schemes.

Keywords: road engineering; life cycle; integrated assessment; improved entropy method; environment and economy

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Citation: Hou, Y.; Qian, X.; Zhang, R.; Gu, F.; Feng, P. Study on an Integrated LCA-LCC Model for Assessment of Highway Engineering Technical Schemes. *Buildings* **2022**, *12*, 1050. https://doi.org/10.3390/buildings12071050

Academic Editors: Yange Li, Huihua Chen, Qing'e Wang and Xiaotong Guo

Received: 18 June 2022
Accepted: 18 July 2022
Published: 20 July 2022

1. Introduction

The "double-carbon" goal of China which commits to peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060 has become a long-term national strategy. According to the Statistical Review of World Energy 2021, carbon emissions in the transportation sector account for 10% of the total, of which carbon emissions in the highway engineering sector account for more than 85% of the transportation sector emissions. These mainly come from machinery operation and the production of engineering materials during the construction period of highway projects, and the fuel consumption of traffic vehicles during the operation period [1]. Therefore, in addition to controlling the exhaust emissions of traffic vehicles during the operation period, optimizing the construction techniques of green highway projects is also an important measure to reduce carbon emissions. In the core work of technical scheme decision-making for highway engineering, it is particularly important to select a technical scheme which functions well, produces less pollution, is economical, and results in the intensive and efficient utilization of resources [2]. However, at present, the assessment of the economic and environmental effects of highway engineering technical schemes is relatively independent and specialized, but it can be difficult to achieve "complex integrity" decision-making. Therefore, it is likely to cause resource consumption, economic waste or environmental pollution. On this basis, constructing a multi-dimensional assessment method that integrates environmental and economic factors has positive significance for promoting the green development of highway construction in China.

In recent years, in terms of the environment of construction projects, scholars at home and abroad start to focus on using the life cycle assessment (LCA) theory to assess the effect of materials on the environment and propose emission reduction measures from the perspective of materials [3,4]. Others focus on constructing carbon emission measurement models of elastic high-speed railway construction or LCA models from the perspective of railway engineering to conduct environmental assessment [5,6]. There are also studies adapting LCA to describe the potential environmental properties of various ecological composite materials, and improve their performance and technology in air transportation [7]. In addition, combine LCA with BIM to quantify the life-cycle waste of prefabricated formwork or evaluate the potential environmental impacts in buildings [8,9]. In terms of its economy, foreign and domestic researchers tend to combine life cycle cost (LCC) with the whole process analysis of structural functionality. For instance, the maintenance measures are taken from the perspective of LCC, and the corresponding scheduling problem framework is constructed [10]. In the airport pavement management system, LCC is used to analyze the direct and indirect costs to provide reference for pavement maintenance and repair strategies [11]. However, whether from the environmental or economic perspective, LCA or LCC analysis from a single perspective has certain limitations for the sustainability analysis of projects. In view of this limitation, research on the combination of LCC and LCA is increasing globally. For example, in material engineering, the sustainable decision-making problem of composite material recycling and new material replacement is analyzed through the combination of the economy and environment [12], or LCA is converted into environmental costs to integrate LCA and LCC, and compare and select multiple materials [13]. In architectural design, through the combination of LCA and LCC, the "Eco" framework has been proposed and applied to architectural design decision-making [14]. In construction engineering, a combined LCA-LCC framework has been proposed to analyze the potential energy and carbon emissions of community housing, and to assess solutions for building renovations [15]. In airport pavement management systems, the LCA-LCC method has been applied to compare alternatives based on economics as well as other perspectives beyond economics [16]. The current methods with the combination of LCC and LCA tend to lack certain integration and timeliness, and the results show some uncertainty in the input parameters [17]. Therefore, some scholars propose the basic idea of integration [18–26]. However, in specific practice, the application of life cycle integration assessment research is narrow. Especially concerning highways, only some greenhouse gases are analyzed. It is difficult to trace to the sources and operate with multi-objective assessment. In addition, these methods conflict in various dimensions, and lack a complete life cycle database with high quality data relevant to China's national conditions [27–33]. In addition, due to the differences in current assessment methodologies, there is no standard to integrate LCA and LCC, and conflicting assessment results lead to confused decision-making [34]. As a result, an LCA-LCC integration assessment model that can solve the above problems and be directly applied to the assessment of highway engineering technical schemes is urgently needed.

The latest documents and data issued by the Ministry of Ecology and Environment, the Ministry of Finance, the State Taxation Administration and the Ministry of Transport of China were selected as an integrated assessment database. A total of 42 indexes measuring waste pollution, noise pollution, energy consumption, pre-project cost, project construction cost, project operation cost and post-project cost were established. The LCA-LCC integration assessment index system was then constructed to expand and improve the highway engineering technical schemes. The two-dimensional combined spatial correlations of the environment and the economy was able to overcome the limitations and imbalances of single-dimensional assessment. Based on the LCA-LCC integration assessment index system, an integrated assessment model of highway engineering technical schemes with an improved entropy method was established and applied to the assessment of highway subgrade and pavement engineering technical schemes. This paper provides a reference for solving multi-dimensional and multi-objective decision-making problems in the assessment of highway engineering technical schemes.

2. LCA-LCC Integration Assessment Index System

The core objective of the LCA-LCC integration assessment model is to enable the decision-makers of highway construction technology to simply and effectively select schemes when faced with various multi-dimensional and multi-objective decisions. It provides a basis for comprehensive, accurate and highly credible decision-making. The establishment of the index system the database is the key to the assessment model. The database of this paper relies on the most current published documents and data, which ensures, to a large extent, that it is complete, open, localized and high-quality. Nine aspects are included: air pollution, water pollution, solid waste pollution, noise pollution, energy consumption, pre-project cost, project construction cost, project operation cost and post-project cost. Additionally, the inclusion of both environmental and economic dimensions ensures the accuracy, comprehensiveness and computability of the index system.

2.1. Selection of Assessment Index

The assessment index plays a vital role in the whole integration process, which is also the key content and main basis of the integrated assessment system. Based on the environmental and economic dimensions, this paper selects the primary and final assessment indexes for highway engineering technical schemes.

Firstly, according to document No. 16 of 2021 issued by the Ministry of Ecology and Environment, the Ministry of Finance and the State Taxation Administration of China, the pollution equivalent value proposed in Article 25 of the Environmental Protection Tax Law of China, the Integrated Wastewater Discharge Standard (GB8978-1996), and the estimated quotas for highway projects and similar documents, a total of 141 primary indexes were determined. These included 66 air pollution indexes, 45 water pollution indexes, 4 solid waste pollution indexes, 6 noise pollution indexes, 3 energy consumption indexes, 5 pre-project cost indexes, 6 project construction cost indexes, 4 project operation cost indexes, and 2 post-project cost indexes.

Then, according to the Table of Taxable Pollutants and Equivalent Values in the Environmental Protection Tax Law of China, the pollutants involved in highway projects were screened and sorted according to their equivalent value. After calculation, pollutants with equivalent values too small to affect the model were excluded. Finally, a total of 42 indexes were chosen, including 11 air pollution indexes, 10 water pollution indexes, 4 solid waste pollution indexes, 3 noise pollution indexes, and 3 energy consumption indexes, 4 pre-project cost indexes, 2 project construction cost indexes, 3 project operation cost indexes, and 2 post-project cost indexes.

2.2. Construction of Assessment Index System

After the final selection of assessment index, the LCA-LCC integration assessment index system was divided into target, criterion, sub-criterion and index layers. Among them, the target layer contains the integration goals of LCA-LCC, and the criterion layer includes the two dimensions of environment and economy. The sub-criterion layer was divided into nine items according to various indexes, pollution types and cost composition, and the index layer was classified according to the characteristics, computability, and operability of each index. The constructed LCA-LCC integration assessment index system is shown in Table 1.

Table 1. LCA-LCC integration assessment index system.

Target Layer	Criterion Layer	Sub-Criterion Layer	Index Layer	Unit
Integrated LCA-LCC assessment	U1 environment	U11 air pollution	U111 Styrene pollution value	kg
			U112 carbon dioxide pollution value	kg
			U113 carbon monoxide pollution value	kg
			U114 hydrogen chloride pollution value	kg
			U115 general dust pollution value	kg
			U116 nitrogen pollution value	kg
			U117 glass wool dust pollution value	kg
			U118 soot pollution value	kg
			U119 sulfur dioxide pollution value	kg
			U1110 hydroxide pollution value	kg
			U1111 industrial waste gas	m^3
		U12 water pollution	U121 chromaticity, PH value, Escherichia coli, residual chlorine pollution values	\
			U122 chemical oxygen demand (COD)	g
			U123 ammonia nitrogen pollution value	g
			U124 biochemical oxygen demand (BOD5)	g
			U125 fluoride pollution value	g
			U126 total organic carbon (TOC)	g
			U127 oil pollution value	g
			U128 volatile phenol pollution value	g
			U129 suspended solids pollution value	g
			U1210 industrial wastewater	ton
		U13 solid waste pollution	U131 coal gangue pollution value	ton
			U132 exhaust pollution value	ton
			U133 hazardous waste pollution value	ton
			U134 pollution value of smelting slag, fly ash, slag and others (including semi-solid and liquid waste)	ton
		U14 noise pollution	U141 pollution value $\leq$ 10 dB	dB
			U142 10 dB < pollution value < 16 dB	dB
			U143 pollution value $\geq$ 16 dB	dB
		U15 energy consumption	U151 renewable resource depletion degree	\
			U152 recyclable non-renewable resource depletion degree	\
			U153 non-recyclable non-renewable resource depletion degree	\
	U2 economy	U21 pre-project cost	U211 project planning fee	yuan
			U212 feasibility study fee	yuan
			U213 design and publicity fees	yuan
			U214 consultation fee	yuan
		U22 project construction cost	U221 direct costs during the project construction period	yuan
			U222 indirect costs during the project construction period	yuan
		U23 project operation cost	U231 operation fee	yuan
			U232 repair fee	yuan
			U233 maintenance fee	yuan
		U24 pre-project cost	U241 scrapping fee	yuan
			U242 recycling fee	yuan

In the assessment model, a total of 42 indexes that measure aspects of the environment and economy were included. All the indexes are negative, that is, the lower the environmental index is, the less pollution to the environment. Likewise, the lower the economic index is, the lower the sample cost.

The environmental dimension was divided into five sub-criterion layers: air pollution, water pollution, solid waste pollution, noise pollution, and energy consumption. The first four indexes can be obtained by calculating pollutants according to the actual plan, or by referring to data according to the discharge (production) pollution coefficient list of the emission source statistical investigation system issued by the Ministry of Ecology and Environment, the taxable pollutants and equivalent value table issued by the *Environmental Protection Tax Law of China* and other documents. The energy consumption was divided into three categories according to whether it is renewable or recyclable [35]. According to Formulas (1)–(3), the renewable, non-renewable and non-recyclable non-renewable resource depletion degrees, designated as HJD_1, HJD_2 and HJD_3, respectively, were calculated:

$$HJD_1 = \frac{UD}{R^2}(1 - RR) \tag{1}$$

$$HJD_2 = \frac{UD(1 - RR)}{SSR \cdot R^2} \tag{2}$$

$$HJD_3 = \frac{UD}{SSR \cdot \lambda \cdot R^2} \tag{3}$$

where U is the unit resource; R is the nationwide storage of the resource; D is the annual consumption of the resource; RR is the recycling rate; SSR is the self-sufficiency rate; λ is the energy quality coefficient of the non-recyclable non-renewable resource, $\lambda = \eta \cdot W/Q$ (η is the average conversion efficiency of primary energy into secondary energy that can be used by products; W is the part of energy of the resource that can be converted into useful work; and Q is the total energy of the non-renewable resource).

The economic dimension was divided into four sub-criterion layers according to the LCC: pre-project cost, project construction cost, project operation cost and post-project cost. The pre-project cost and project operation cost were tracked, collected and calculated based on specific case samples or local similar cases selected to collect data by analogy. The project construction cost and post-project cost were collected according to the estimated quota of highway projects, local market prices, and budget tables provided by specific project construction units. After the data was collected, it was discounted to the same time point to adjust for the economic effects of time.

3. LCA-LCC Integration Assessment Model

3.1. LCA-LCC Integration Assessment Framework

The LCA research boundary is wider and encompasses all activities from the analysis of the environment in the feasibility study to when the project is scrapped and recycled, whereas the LCC analysis begins with the project planning and terminates at the end of the project. Since their boundaries are different, the primary condition for integration is to determine the common research boundary of the two. In this paper, the LCA-LCC integration assessment boundary was set from the feasibility study to the scrapping or recycling stage, and thus, the LCA-LCC integration assessment framework was constructed. As shown in Figure 1, through the analysis of different samples, the integrated research section (usually the difference between the research samples) was determined, and then the estimated inventory data were outputted through the environment and cost of research sections. Since the construction period in highway engineering is long and the time span of cost occurrences is large, it was decided to discount the cost incurred in different time periods to the same time point, conduct integrated processing and assessment on the data, and finally conduct a sort according to the integrated assessment index. Thus, the most optimal scheme was determined.

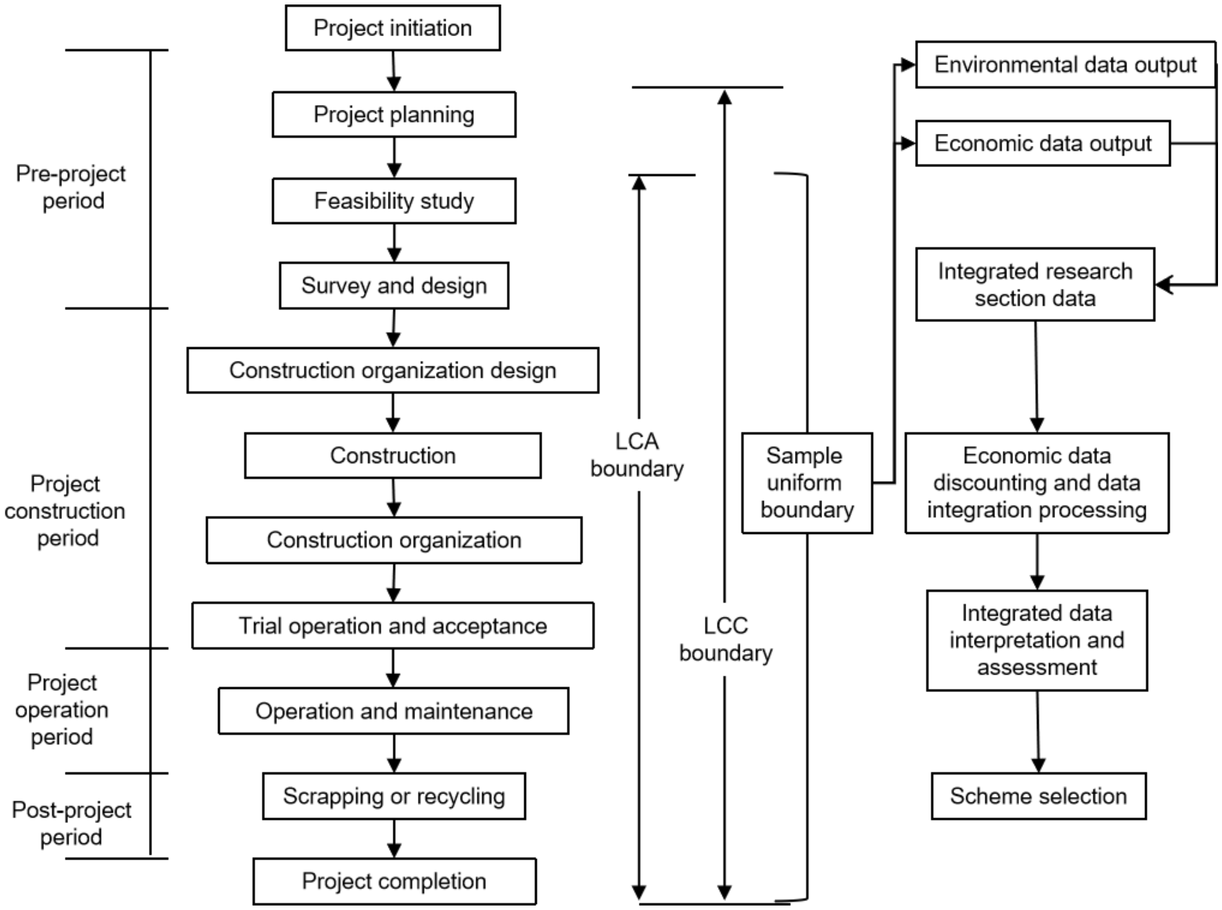

Figure 1. LCA-LCC integration assessment framework.

3.2. Construction of LCA-LCC Integration Assessment Model

For such a multi-dimensional and multi-index assessment system, the entropy method is the most commonly used for assessment in China. The entropy method [36–38] determines the weightings according to the amount of information provided by the sample, and it is considered a highly credible and objective assessment method. However, the running process of the original entropy method has some drawbacks, such as ambiguous results when there are few assessment schemes, the inoperability of the method with negative and zero values, and unbalanced multi-dimensional and multi-aspect assessments. In terms of these problems, the entropy method was improved as follows:

1. The data were standardized. In the integrated assessment index system, each index of the index layer was set as a negative assessment index, that is, the larger the assessment index value, the larger the pollutant discharge or the higher the cost. Conversely, the smaller the value, the closer the index value is to the optimal minimum value. If 0 and negative values are encountered in the calculation, the translation adjustment of dividing by 0 and negative values must be conducted. Additionally, if a multi-dimensional and multi-angle scheme assessment is encountered, a parallel calculation of partition equilibrium must be performed so as to avoid index deviation as follows:

$$\text{Negative assessment index}: \ U_{ij}^{*} = \frac{U_{\min}}{U_{ij}} \tag{4}$$

$$\text{Normalized value}: \ B_{ij} = \frac{U_{ij}^{*}}{\sum\limits_{i=1}^{n} U_{ij}^{*}}, (i = 1, 2, \ldots, n, j = 1, 2, \ldots, m) \tag{5}$$

$$\text{Normalized matrix}: \ B = \{B_{ij}\}_{n*m} \tag{6}$$

where m is the assessment index of the sample; n is the object of the assessment scheme; i is the i-th object of the assessment scheme; j is the j-th assessment index; and $U_{\min}$ is the minimum value in each assessment index scheme, which is calculated by using the above formulas.

2. The information entropy value $X(U_j)$ of the assessment index was calculated as follows:

$$X(U_j) = -K\sum_{i=1}^{n} B_{ij}\ln B_{ij}, i = 1,2,\ldots,n, j = 1,2,\ldots,m, \ \ 0 < X(U_{\text{i}}) < 1 \tag{7}$$

where K is the adjustment degree, $K = \frac{1}{\ln n}$. The more assessment schemes there are, the lower the adjustment degree. The larger the difference between the index values, the smaller the entropy value, and the better the assessment effect of the sample.

3. The difference coefficient value Y_j of each assessment index was calculated.

$$Y_j = 1 - X(U_j), j = 1,2,\ldots,m, 0 < Y_j < 1 \tag{8}$$

4. The weight W_j of the assessment index was calculated.

$$W_j = \frac{Y_j}{\sum\limits_{j=1}^{m} Y_j}, (1 \le j \le n) \tag{9}$$

5. The integrated assessment index Z_i of each scheme was calculated.

$$Z_{\text{i}} = \sum_{i=1}^{n} W_j * B_{ij}, i = 1,2,\ldots,n, j = 1,2,\ldots,m \tag{10}$$

The larger the value of Z_{i}, the higher the integrated assessment index and the better the sustainability of the sample.

4. Application Cases

Two asphalt pavement maintenance schemes of Highway US280 in Alabama and two improved schemes of high liquid limit soil subgrade of Highway G360 in Hainan were selected as objects. The sustainability assessment of environmental and economic dimensions was carried out, and the feasibility and practicality of this method were verified.

4.1. Assessment of Two Asphalt Pavement Maintenance Technical Schemes

1. Introduction to the alternative schemes

As large numbers of early asphalt pavements enter the late stages of service, various properties of the pavement decline substantially. Therefore, large-scale maintenance work is urgently needed. Among various regeneration technologies, it is necessary to select a technology with a high utilization rate of old materials, small environmental impacts, and low costs as an effective way to solve this problem [39,40].

In this study, Highway US280 in Alabama, USA was selected as an example [41], and the LCA-LCC integration assessment method was used to evaluate two asphalt pavement maintenance methods, namely the hot-mix new asphalt mixture technical scheme (referred to as the SMA scheme, scheme 1) and the emulsified asphalt in situ cold recycling technical scheme (referred to as the cold recycling scheme, scheme 2). The sustainability assessment of environmental and economic dimensions was also carried out. For both technical schemes, the plant mixing method was selected. According to the current specification requirements, the construction process is shown in Figure 2.

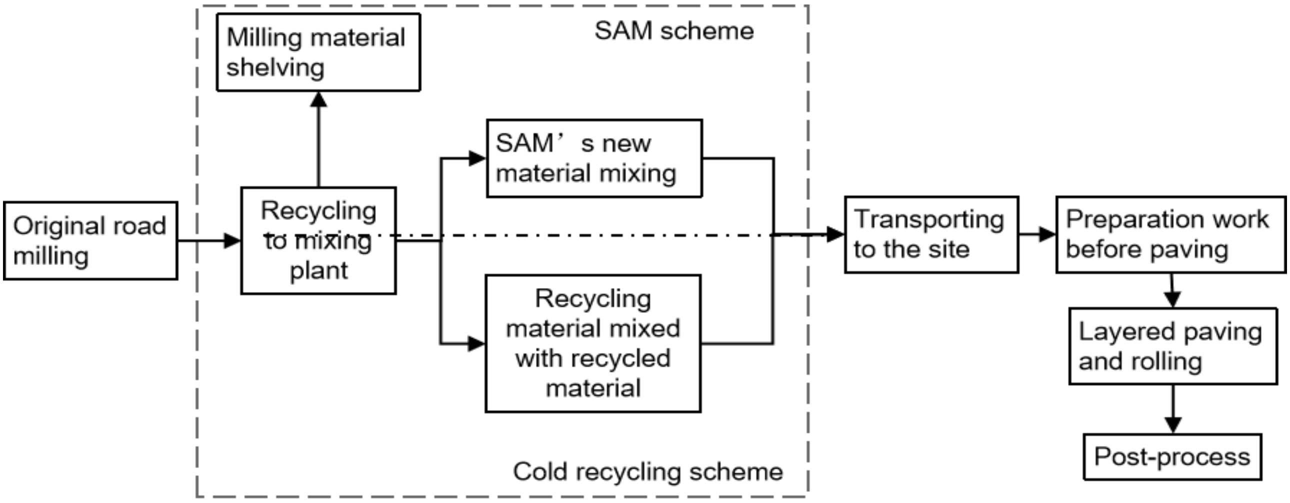

Figure 2. Construction technique of asphalt pavement maintenance technology.

2. Boundary division

For reasons of feasibility, the study scope was also simplified, and the following main assumptions were made: At first, the major work activities of the two schemes were assumed to be the same. These works include the design and planning of project preliminary work, the treatment of the pavement substructure, the original pavement milling, the transportation of milled materials to mixing plant, the delivery of new materials, the preparation work before pavement, the maintenance work, the operation and maintenance, etc. Secondly, the upper wear layer of the two schemes was also assumed to be identical. Thus, this part of the work was not calculated when the scheme was selected, and this assessment was only applied for various parts of the pavement that differed between the two schemes. In addition, various auxiliary materials were used in the construction of the subgrade. If these were in low proportions, they were not included in this assessment. Finally, if any pollutant was emitted in quantities too low to measure and had little impact on the environment, it was not included in this assessment.

3. Data collection and single dimension assessment

Based on the documents issued by the Ministry of Ecology and Environment, the project budget and settlement documents and other documents, the emissions and economic data of the two schemes were also collected, as shown in Table 2 below.

According to calculations, it was found that the cold recycling scheme requires additional cement, and that the mining and processing of cement lead to atmosphere and water pollution. However, in terms of the utilization of recyclables after milling, the hot-mix new asphalt mixture consumes large quantities of sand and gravel, and the mining and processing of sand and gravel have a greater impact on energy consumption and construction costs. However, the high utilization rate of milling recyclables in the cold recycling scheme results in large savings in energy consumption and reduces the construction costs.

If a single-dimensional assessment method is used, the LCA results of Scheme 1 are superior to those of Scheme 2, whereas the LCC results of Scheme 2 are better than those of Scheme 1. Therefore, decision makers cannot guarantee the comprehensiveness and balance of the assessment results based on the separate LCA or LCC methods alone.

4. LCA-LCC integration assessment

The collected data were normalized, and the entropy method was applied to calculate the weight of each index in Table 3.

Table 2. SMA scheme and cold recycling scheme data.

Single Dimension	Type of Pollution	Unit	Emissions	
			SMA Scheme 1	Cold Recycling Scheme 2
LCA model	General dust pollution value	kg	0.00	55.42
	Nitrogen pollution value	kg	0.00	0.41
	Soot pollution value	kg	0.55	53.94
	Sulfur dioxide pollution value	kg	6363.02	5306.03
	Industry exhaust	m^3	121,831.12	100,649.55
	Chemical oxygen demand (COD)	g	4107.33	2350.84
	Ammonia nitrogen pollution value	g	12,278.81	10,218.53
	Fluoride pollution value	g	0.00	11.24
	Oil pollution value	g	1131.09	890.61
	Volatile phenols pollution value	g	31.23	25.78
	Industrial waste	ton	5.00	2.58
	Pollution value of smelting slag, fly ash, slag and others (including semi-solid and liquid waste)	ton	0.01	0.01
	Noise pollution value $\leq$ 10 dB	dB	10.00	10.00
	Noise pollution value $\geq$ 16 dB	dB	70.00	77.00
	Renewable resource depletion degree	/	5.66121×10^{-11}	2.17093×10^{-13}
	Non-recyclable non-renewable resource depletion degree	/	1.95613×10^{-12}	5.95922×10^{-14}
LCC model	Direct costs during the project construction period	yuan	172,611	103,774
	Indirect costs during the project construction period	yuan	32,261	22,643

Table 3. LCA-LCC data and weight.

	Type of Pollution	Weight	Normalized Value	
			SMA Scheme 1	Cold Recycling Scheme 2
LCA-LCC index data	General dust pollution value	3.44	1.00	0.00
	Nitrogen pollution value	3.36	1.00	0.00
	Soot pollution value	3.16	0.99	0.01
	Sulfur dioxide pollution value	0.02	0.45	0.55
	Industry exhaust	0.02	0.45	0.55
	Chemical oxygen demand (COD)	0.47	0.36	0.64
	Ammonia nitrogen pollution value	0.05	0.45	0.55
	Fluoride pollution value	8.68	1.00	0.00
	Oil pollution value	0.09	0.44	0.56
	Volatile phenols pollution value	0.06	0.45	0.55
	Industrial waste	0.65	0.34	0.66
	Pollution value of smelting slag, fly ash, slag and others (including semi-solid and liquid waste)	10.00	0.45	0.55
	Noise pollution value $\leq$ 10 dB	0.50	0.10	0.10
	Noise pollution value $\geq$ 16 dB	9.50	0.52	0.48
	Renewable resource depletion degree	5.44	0.00	1.00
	Non-recyclable non-renewable resource depletion degree	4.56	0.03	0.97
	Direct costs during the project construction period	29.64	0.35	0.65
	Indirect costs during the project construction period	20.36	0.37	0.63

Based on the normalized values and weights of the LCA-LCC method, the integrated assessment index was also calculated and ranked, as shown in Table 4.

Table 4. Integrated assessment index ranking.

No	Alternative Schemes	Integrated Assessment Index							Ranking
		Air Pollution	Water Pollution	Solid Waste Pollution	Noise Pollution	Energy Consumption	Project Construction Cost	Total	
Scheme 1	SMA scheme	9.94	9.16	4.55	5.23	0.16	17.92	46.95	2
Scheme 2	Cold recycling scheme	0.06	0.84	5.45	4.77	9.84	32.08	53.05	1

If a single-dimensional assessment method is adopted, Scheme 1 is superior to Scheme 2 in terms of the environmental aspects, whereas Scheme 2 is superior to Scheme 1 considering the economic aspect. Using the integrated assessment model of LCA-LCC, the integrated assessment index of Scheme 1 is 46.95, and that of Scheme 2 is 53.05. It can be seen from the integrated assessment based on the two dimensions of environment and economy that the cold recycling technical scheme is superior to the hot-mix new asphalt mixture technical scheme.

4.2. Assessment of Two Improved Technical Schemes for High Liquid Limit Soil Subgrade

1. Introduction to alternative schemes

In China, high liquid limit soil is widely distributed, especially in the high rainfall areas of southern China. High liquid limit soil with poor water permeability has high strength when dry, clear capillary properties, expansion and softening after contact with water, poor stability, and low bearing capacity. Therefore, it cannot be directly used as fillers for subgrade and roadbed [42,43]. At present, the commonly used methods for treating high liquid limit soil in China include the mixing of coarse aggregates or the mixing of ash.

In this study, the National Highway G360 from Wenchang to Anding was selected as an example. The LCA-LCC integrated assessment method was used to assess the environmental and economic sustainability of filling methods (improved high liquid limit soil schemes with 4% of cement or 25% of gravel) for two upper subgrades. The plant mixing method was considered in the two technical schemes. Based on the current specification requirements, the construction process was determined and is shown in Figure 3:

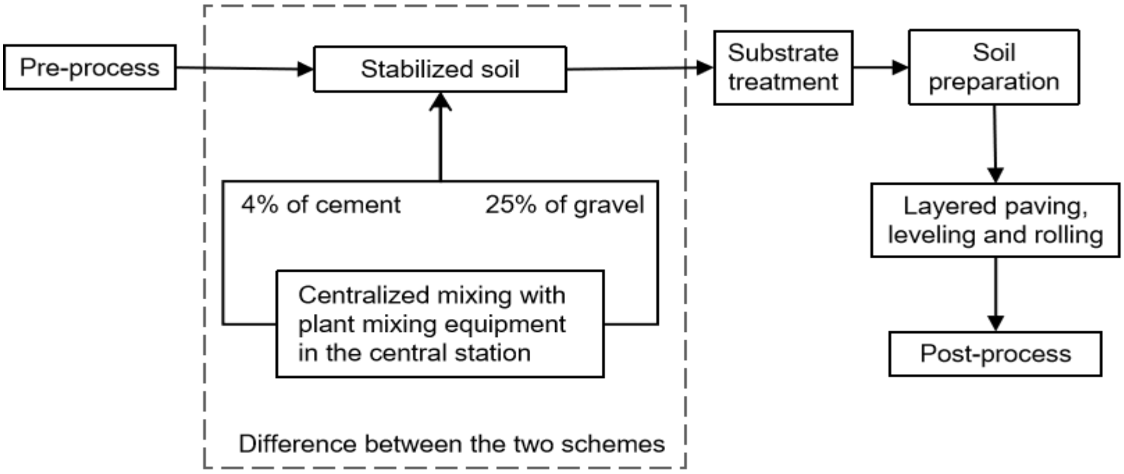

Figure 3. Construction technique of stabilized earth subgrade filling technology.

2. Boundary division

For reasons of feasibility, the study scope was simplified several assumptions were made. Firstly, the main work activities of the two schemes was assumed to be the same. These works included the following: the design and planning of project preliminary work;

the construction of the subgrade, roadbed, road surface; preparation work before subgrade filling; maintenance work after subgrade filling; and operation and maintenance. Therefore, these components of the work were not included in the model calculations to select the scheme. This assessment was applied only to the different parts of the two schemes for the subgrade. Secondly, various auxiliary materials were added in the construction of subgrade. If the proportion of these materials was low, such as a small number of steel bars or geotextiles, etc., they were not included in the assessment. Finally, if pollutants with small quantities of emissions were difficult to measure and had little impact on the environment, they were also excluded from the assessment.

3. Data collection and single dimension assessment

The emissions and economic data of the two schemes were collected (see Table 5).

Table 5. Cement scheme and gravel scheme data.

Single Dimension	**Type of Pollution**	**Unit**	**Emissions**	
			Cement Scheme	**Gravel Scheme**
LCA model	Industrial dust	kg	508,951.2	0
	Nitrogen oxides	kg	3793.716	0
	Soot	kg	495,368.76	0
	Sulfur dioxide	kg	5479.812	0
	Industrial waste gas volume	m^3	412,78128	0
	Chemical oxygen demand (COD)	g	65,570.4	118,968.32
	Ammonia nitrogen pollution value	g	0	2813.44
	Fluoride	g	103,195.32	0
	Oil pollution value	g	0	5827.84
	Volatile phenols	g	0	30.144
	Industrial wastewater volume	ton	2185.68	200.96
	Noise pollution value $\leq$ 10 dB	dB	10	10
	Noise pollution value $\geq$ 16 dB	dB	77	70
	Renewable resource depletion degree	/	1.99×10^{-9}	5.19×10^{-9}
	Non-recyclable non-renewable resource depletion degree	/	5.47×10^{-10}	1.79×10^{-10}
LCC model	Direct costs during the project construction period	yuan	12,191,309	11,346,630
	Indirect costs during the project construction period	yuan	2,281,919	2,059,664
	Recycling costs	yuan	0	−1,728,546.7

According to the model calculations, it was found that the Scheme 1 is far lower than the Scheme 2 in terms of air pollution. The main reason is that a large number of pollutants are emitted when the cement is processed and produced. These include industrial dust, nitrogen oxides, soot, sulfur dioxide and industrial waste gas, all of which have an impact on the atmosphere. In terms of water pollution, Scheme 2 is superior to Scheme 1 because the mining and production of gravel produce COD, ammonia nitrogen, petroleum and volatile phenols and other substances leading to water pollution. The noise pollution of the two schemes results from various construction machinery, such as air compressors, etc.. In terms of energy consumption, the depletion degree of renewable resources (diesel, water) and non-renewable and non-recyclable resources (coal) are mainly considered. Considering the post-project costs, Scheme 2 has much higher costs than Scheme 1 because the gravel is recycled at a 50% recovery rate. Based on a general road service life of 20 years and the 2022 market quotation interest rate issued by the Bank of China, 3.7% per year of the cost is discounted to the construction period.

Based on the model calculations, it is shown that Scheme 2 is superior to Scheme 1 in terms of air pollution, energy consumption, project construction cost and post-project costs, whereas Scheme 1 is superior in terms of water pollution and noise pollution. If a single-dimensional assessment is used, decision makers are not able to make reasonable decisions.

4. LCA-LCC integrated assessment

The improved entropy method was used to compute the weight of each index, as shown in Table 6 below.

Table 6. LCA-LCC data and index weights.

	Type of Pollution	Weight	Normalized Value	
			Cement Scheme	Gravel Scheme
LCA-LCC index data	Industrial dust	2.44	0.01	0.99
	Nitrogen oxides	2.74	0.00	1.00
	Soot	2.74	0.00	1.00
	Sulfur dioxide	1.84	0.06	0.94
	Industrial waste gas volume	2.74	0.00	1.00
	Chemical oxygen demand (COD)	1.57	0.08	0.92
	Ammonia nitrogen pollution value	0.16	0.64	0.36
	Fluoride	2.69	0.00	1.00
	Oil pollution value	2.69	1.00	0.00
	Volatile phenols	2.69	1.00	0.00
	Industrial wastewater volume	2.69	1.00	0.00
	Noise pollution value $\leq$ 10 dB	6.58	0.81	0.19
	Noise pollution value $\geq$ 16 dB	5.92	0.80	0.20
	Renewable resource depletion degree	5.41	0.72	0.28
	Non-recyclable non-renewable resource depletion degree	7.09	0.25	0.75
	Direct costs during the project construction period	8.24	0.48	0.52
	Indirect costs during the project construction period	16.76	0.47	0.53
	Recycling costs	25.00	0.00	1.00

According to the LCA-LCC normalized values and weights, the integrated assessment index was also computed and rate ranked (see Table 7).

Table 7. Integrated assessment index ranking.

No	Alternative Schemes	Integrated Assessment index							Ranking
		Air Pollution	Water Pollution	Noise Pollution	Energy Consumption	Project Construction Cost	Post-Project Cost	Total	
Scheme 1	Improved high liquid limit soil subgrade with 4% of cement mixed	0.13	8.30	10.07	5.67	11.83	0.00	36.01	2
Scheme 2	Improved high liquid limit soil subgrade with 25% of gravel mixed	12.37	4.20	2.43	6.83	13.17	25.00	63.99	1

According to the integrated assessment model with both environmental and economic dimensions presented in this paper, the integrated assessment indexes for Scheme 1 and Scheme 2 were 33.87, and 66.13, respectively. It can be seen that the sustainability of the technical scheme which adds 25% of gravel to improve the high liquid limit soil subgrade is clearly better than that based on a 4% cement mixture. This conclusion can provide an effective basis for decision makers in the selection of highway construction technology for Highway G360 in Hainan.

5. Conclusions

1. The latest documents, issued by the Ministry of Ecology and Environment, the Ministry of Finance, the State Taxation Administration, the Ministry of Transport of China,

were selected as the basis of an integrated assessment database. Each process in highway construction was then calculated under the same dimension. The data obtained can be used to ensure the requirements of the green economy are met. The data can also be directly applied in calculating the daily pollutant taxes of enterprises, which can avoid the need for repeated calculations and realize the generalization of data.

2. A total of 42 life cycle environmental and economic assessment indexes of highway engineering technical schemes were screened for nine aspects: air pollution, water pollution, solid waste pollution, noise pollution, energy consumption, pre-project cost, project construction cost, project operation cost, and post-project cost. Thereby, a corresponding index system was established.
3. An integrated assessment model of the environment and economy was proposed, and the integrated research boundary was unified. The LCA-LCC integration assessment model suitable for highway technical schemes was constructed using the improved entropy method, which could be helpful for decision makers to obtain comprehensive, accurate and effective insights.
4. The integrated assessment model proposed in this paper was applied in the assessment of asphalt pavement maintenance schemes of Highway US280 in Alabama and improvement schemes for the high liquid limit soil subgrade of Highway G360 in Hainan, which verified the feasibility, practicality and versatility of the assessment model.
5. In the assessment of specific technical schemes, due to the effects of the region and the characteristics of highway project itself, the selection of assessment indexes can be adjusted on the basis of the index system established in this study. In the future, both breadth and depth will be considered in the assessment method, and classification and verification studies will also be carried out for different types of highway projects to further improve the integrated assessment system.

Author Contributions: Conceptualization, Y.H., X.Q. and R.Z.; methodology, Y.H., X.Q. and R.Z.; validation, Y.H. and X.Q. and R.Z.; formal analysis, P.F.; investigation, F.G.; resources, F.G. and X.Q.; data curation, X.Q.; writing—original draft preparation, Y.H. and X.Q.; writing—review and editing, Y.H. and X.Q.; visualization, Y.H. and X.Q.; supervision, R.Z.; project administration, Y.H. and X.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant No. 51978085, 52108400); and the National Natural Science Foundation of Hunan Province (Grant No. 2020JJ4629); the Research and Development Program of China National Railway Croup Co. Ltd; Project (Grant No. 2020G036).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: http://www.chinatax.gov.cn/chinatax/n610/c5164066/content.html (accessed on 17 June 2022).

Conflicts of Interest: The authors declare no conflict of interest.

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