Hindawi
Modelling and Simulation in Engineering
Volume 2018, Article ID 4172519, 8 pages
https://doi.org/10.1155/2018/4172519

Research Article

Reliability Evaluation of Pavement Life-Cycle Assessment Model

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Received 10 May 2018; Accepted 26 September 2018; Published 18 October 2018

Academic Editor: Ricardo Perera

Inventory reliability of the life-cycle assessment (LCA) model highly depends on the data quality and normally exhibits significant uncertainty. A rigorous statistical methodology was established to capture and quantify the inherent uncertainties linked to the results of the LCA model. Two sources of uncertainty, data quality and model, were identified. The former was captured by converting the deterministic value to probability density function using beta distribution according to the evaluation matrix of data quality; the latter was assessed by prescribing variation interval through defining uncertainty factor. The functional equivalent pavement structures were designed, and the corresponding energy consumption and CO_2 emission were calculated by the LCA model. A 10% variation was observed for the LCA results and within 30-year analysis span, at the 95% confidence level, and environmental burdens of cement pavement are higher than those of asphalt pavements while the comparison between the two asphalt pavements is not significant statistically. Therefore, the established statistical methodology is capable of capturing the uncertainty of the LCA model and quantifying the reliability the LCA results.

1. Introduction

At present, energy conservation and emission reduction in transportation engineering have become the most important aim in China development planning. However, it is just a macroscopic one. Therefore, a data base about the CO_2 emission and energy consumption is needed to accurately assess the effect of technologies for energy conservation and emission reduction. Besides, developing an evaluation template on the bituminous pavement construction and the benefit of environmental protection of maintenance technology is also necessary [1]. Conducting studies on the evaluation system of technologies for energy conservation and emission reduction can provide theoretical foundation and technical support for evaluating the effect of technologies for energy conservation and emission reduction. Therefore, it is extremely necessary to carry out the relevant studies.

The rapid development of road construction brings about serious environmental issues, such as energy consumption, CO_2 emission, and land occupancy [2]. Thus, quantifying and reducing the influence of roadway on environment in its lifetime becomes gradually important and attracts wide attention [3, 4]. As a tool for assessing environmental implication, the life assessment (LCA) has been widely used in roadway engineering and becomes the main tool for analysis of influence of roadway on environment [5–7]. However, some weaknesses exist in the theory of LCA, particularly the uncertainness of data quality and model [8]. The accuracy of LCA for roadway or else objects depends on data and model parameters with high quality. Due to the absence of data and their reliability, the data utilized in LCA are not necessarily the expected one. Therefore, even though optimal data can be acquired or certain existing data can be combined, a trade-off has to be adopted. For example, the authors have collected numerous information and found that the consumption intensity for cement production is 4.6–7.3 MJ/kg and that for bitumen production is 0.7–6.0 MJ/kg. The great difference is shocking and resulted from the differences between system boundary, manufacturing technique, and manufacturing process in the local area. Besides, for bitumen material, the environmental influence depends on the distribution of different chemical products, such as petrol, diesel oil, and plastics.

The difference of distribution style results in significantly different results [9–11]. In the process of LCA establishment, the assumption and simplification are involved, which also affect the reliability of assessment results of environmental influence.

Therefore, based on a practical case, a LCA model was developed and the influence of roadway on the environment was carried out. The uncertainness of assessment results of the LCA model is captured from the perspective of data quality and model assumption to establish a rigorous methodology for reliability assessment of results of the LCA model.

2. The Establishment of LCA Model

Roadway is a complex structure and susceptible to several external factors, such as climate, transportation intensity, and the production and transportation of material. Thus, the authors took advantage of the existing data model and established a LCA model which includes the following module:

(1) Material production module: consideration on the process involved in the material production

(2) Transportation module: description about the environmental influence during the material transportation

(3) Construction maintenance module: consideration on the oil consumption of facilities and its environmental influence

(4) Postprocessing module: different postprocessing scenes can be used according to the system boundary and the setup of consumption

The function unit of the LCA model is set in an analysis cycle of 30 years and the service performance is applicable to a roadway with single lane and a length of 1000 m.

3. Methodology for Reliability Evaluation

The application of LCA depends on large amounts of data input which defined the characters of the model such as specification for road design, input and output stream of material energy, and environmental impact. The results of LCA are highly dependent on the reliability of input parameters with a certain degree of uncertainty inevitably. This investigation establishes corresponding methodologies for quantitative assessment from data uncertainty and model uncertainty.

3.1. Data Uncertainty. The factors of data uncertainty are divided into experiential evaluation, measurement error, and nonrepresentativeness which includes data obsoleting and excessive technical differences, even data missing. Ideally, the solution to data uncertainty is establishing corresponding probability density function by collected data and putting it into LCA. However, the measurement data, samples, and experience that we need are usually rare. In this case, the descriptive index was employed to assess the quality of data, which forms the data quality evaluation matrix as shown in Table 1.

The data quality index (DQI) can be obtained by the established data quality system matrix. The DQI can be converted to probability density function as input parameters of uncertainty analysis, specifically shown as follows:

$$\begin{aligned} f(x;\alpha,\beta,a,b) = {} & [1/(b-a)] \times \{\Gamma(\alpha+\beta)/\Gamma(\alpha)\times\Gamma(\beta)\} \\ & \times [(x-a)/(b-a)]^{\alpha-1} \\ & \times [(b-x)/(b-a)]^{\beta-1} \quad (a \le x \le b), \end{aligned} \tag{1}$$

where α and β are the shape parameters of distributions and a and b are the interval end points.

The reasons why choosing beta function are shown as follows:

(1) The shape and probability of the distribution established by shape parameters are unknown, and endpoint parameters limit the range of prefabrication

(2) The distribution shape of the beta function is various due to the shape and endpoint parameters.

3.2. Model Uncertainty. The inherent uncertainty of the model associated with the decision affects the analysis results of the LCA. The model refers to the concept of generalization and has a wide range of extensions. It can be either a specific regression model, for example, prediction of asphalt mixing energy consumption, or input parameter assumptions, such as the amount of asphalt used in grading design and the organization of construction platoons. For the variability of LCA model input values, such as the ratio of oil and stone and transportation distance, it can be described by defining "uncertainty factor (UF)" where the uniform distribution and lognormal distribution are common distribution forms.

For the uniform distribution, the minimum and maximum values of the input parameters M_x are defined using the following equation:

$$\begin{cases} M_{x,\min} = \dfrac{M_{x,\mathrm{mod}}}{\mathrm{UF}_x}, \\ M_{x,\max} = \mathrm{UF}_x \times M_{x,\mathrm{mod}}, \end{cases} \tag{2}$$

where $M_{x,\min}$, $M_{x,\max}$, and $M_{x,\mathrm{mod}}$ are the minimum, maximum, and modus, respectively.

For the lognormal distribution, the fluctuation range of the input parameters M and UF are defined in the following equation:

$$p\left(\frac{M_{x,\mathrm{mod}}}{\mathrm{UF}_x} < M_{x,\mathrm{mod}} < \mathrm{UF}_x \times M_{x,\mathrm{mod}}\right) = 0.95, \tag{3}$$

where the parameters are defined in Equation (2).

4. Case Analysis

This case analyzed the energy consumption and carbon emissions of highways cement pavement structure and asphalt pavement structure during their life cycle under the

Table 1: Data quality evaluation matrix.

Quality grade	Judgement standard						
	Selection standard	Technology correlation	Location correlation	Data sources	Acquiring methods	Time	Representation of data
5	Transparent, verified, and generally applicable	Representative process and representative technology	Represent value of local area	Verified data from independent source	Actual measurement	<3 years	Long time and large sample
4	Transparent, verified, and no generally applicable	Representative process and similar technology	Average value of local area	Verified data from relevant source	Measurement-based calculation	<6 years	Long time and small sample
3	Transparent, no verified, and no generally applicable	Representative process and different technology	Other area with similar production process	Unverified data from independent source	Hypothesis-based calculation	<10 years	Short time and large sample
2	Selective transparent and no selection standard	Similar process and similar technology	Other area with slightly similar production process	Unverified data from irrelevant source	Expert estimation	<15 years	Short time and small sample
1	Unknown selection standard	Similar process and different technology	Unknown location	Unverified data from relevant source	Calculation with no guaranteed quality	>15 years	Cannot be obtained

same traffic volume and weather conditions and demonstrated the reliability of the calculation results.

4.1. Waterway Asphalt Pavement Structure Design. For highways with asphalt pavement structures, the design period is generally 15 years. For cement highway structures, the design period is generally 30 years. In order to make the environmental impact analysis consistent, the functional unit is set to provide an acceptable road service performance for a single-lane one-kilometer-long road surface in a 30-year analysis cycle. The design index of the road structure tends to and does not exceed the design tolerance value. For asphalt pavement structural design, there are two situations:

(1) The design life of asphalt pavement structure is set to be 30 years to achieve a certain degree of long-life asphalt pavement design.

(2) The asphalt pavement design period is 15 years. Assuming that, in the 15th year, the basement structure of the asphalt pavement was not damaged, only the asphalt surface structure was resurfaced by milling.

In order to ensure the functional equivalence of the cement and asphalt pavement structures, the pavement structure needs to be carefully designed so that the control index of the pavement structure approaches its limit at the end of the design life cycle, ensuring that the pavement structure has neither "excessive design" nor "insufficient design". Under this guiding principle, the equivalent design parameters of cement and asphalt pavement structures are shown in Table 2.

Although the asphalt pavement designed for 30 years of life will not suffer structural damage, it is still necessary to periodically perform conservation actions to ensure the functionality of the surface structure. At present, China has not established a strict decision-making system for pavement maintenance. Therefore, the conservation manual in California is referred to maintain the three types of pavement structure [13]. The maintenance plan is as follows:

(1) For an asphalt pavement structure with a design life of 30 years, a 2.5 cm thick overlaying in thin layer is laid at the end of the 20th year, and a 4 cm-thick pavement structure is milling-resurfaced at the end of the 24th year

(2) For an asphalt pavement structure with a design life of 15 years, a 6 cm-thick pavement structure is milling-resurfaced at the end of the 15th year, a 4 cm-thick overlaying in thin layer is laid at the end of the 20th year, and a 4 cm-thick pavement structure is milling-resurfaced at the end of the 25th year

(3) For a cement pavement structure, the pavement structure is replaced with the cement board at the end of the 15th year and the end of the 25th year, respectively

4.2. Calculation Based on LCA Model. The environmental impact on each module has been computed based on the LCA model constructed before. The calculation factors include energy consumption and CO_2 emissions, using unit mass standard coal (kgce) and kg-CO_2 as their unit, respectively.

4.2.1. Material Producing Module. Environmental impact of unit productivity on road materials has been determined through document retrieval, theoretical calculations, and on-site inspections, and the result is shown in Table 3.

According to the pavement structure design maintenance parameters and Table 3, the environmental impact on material producing module can be obtained.

Table 2: Converting matrix of probability density function [12].

DQI		5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Parameters of beta distribution	Shape function	(5,5)	(4,4)	(3,3)	(2,2)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)
	Interval endpoint	10	15	20	25	30	35	40	45	50

Table 3: Design parameters of pavement structure.

Pavement structure	Upper layer (cm)	Middle layer (cm)	Lower layer (cm)	Base (cm)	Subbase (cm)	Designed deflection (0.01 mm)	Calculated deflection (0.01 mm)
Asphalt (30 years of design)	6	8	12	40	25	14.0	13.5
Asphalt (15 years of design)	4	6	8	30	25	17.2	16.8
Cement	Surface course (cm)	Base course (cm)	Fatigue stress of surface course (MPa)		Maximum multiple stress of surface course (MPa)	Flexural tensile strength of surface course (MPa)	
	30	20	4.89		2.94	5.0	

4.2.2. Transportation and Construction Module. As for the calculation of the environmental impact on transportation and construction modules, we choose JTG/T B06-02-2007 and JTG/T B06-03-2007 as the fundamental documents. The main steps are as follows: first, determining the number of per-unit-production of mechanical shifts according to the construction process flow stipulated in the budget quota; second, determining the total energy consumption by the energy consumption parameters of the unit machinery and equipment specified by the mechanical station cost quota; the last but not the least, calculating per-unit energy consumption.

4.2.3. Postprocessing Module. The asphalt pavement and cement pavement reach the end of design life after the 30-year life cycle. Thus, for the asphalt pavement, the pavement layer needs to be milled and the RAP needs to be transported to mixing building, and for the cement pavement, the pavement layer needs to be smashed and the RCM needs to be transported to the accumulation point, where the transportation distance is assumed to be 25 km.

4.2.4. Calculation Results of LCA Model. Calculation of the environmental impact of the cement asphalt pavement structure under life cycle with the LCA model is done, and the results are shown in Table 4.

It can be seen that the stage of producing pavement material consumed the most energy and released the most CO_2 in all structures with any pavement. By comparing the structure with the asphalt pavement (15-year or 30-year design) and the cement pavement, the structure with the cement pavement consumes less energy and emits less CO_2, which means the cement pavement structure has a greater probability of reducing the environmental impact during the life cycle.

In this paper, two life-cycle asphalt pavement structures were designed. The asphalt roads with a design life of 15 years have less impact on environment than those with a design life of 30 years, but the difference is not so significant. Also, such conclusion is closely dependent on the parameter assumptions in the LCA modeling process and needs further confirmation.

4.3. Reliability Analysis for LCA Model. There remains some uncertainty during modeling the LAC model due to data quality defects and model parameters assumptions, which are needed to be evaluated.

4.3.1. Data Uncertainty Analysis. With the data quality assessment methodology established in Section 3.1, the quality of road material environmental data was evaluated. Taking bituminous materials as an example, the energy consumption of matrix asphalt production is 170.34 kgce.

The calculation for energy consumption of base-asphalt production uses the calculation model of Eurobitume 2011 and the data of China Statistical Yearbook as reference. Therefore, the evaluation scores for the indicators according to Table 1 are {3.0, 5.0, 4.0, 4.0, 3.0, 5.0, 3.0}, and thus its DQI is 3.85. By using Table 5 as a reference, the parameter of beta function can be de defined. Its shape function α, β is (3,3), and the interval endpoint is (−20%, +20%). The probability density function of the production of matrix asphalt materials is shown in Figure 2.

According to the probability density function established in Figure 2, the energy consumption value and reliability of the matrix asphalt materials can be evaluated. Analogously, a probability density function curve can be established for the production of carbon emissions from matrix asphalt materials and other road material, providing a data source for the Monte Carlo analysis.

4.3.2. Model Uncertainty Analysis. During modeling, parameters like transportation distance and asphalt mixture

Table 4: Energy consumption and CO_2 emission of pavement materials in China.

Material	Energy consumption (kgce/t)	CO_2 emissions (kg/t)	Data source
Asphalt	170.34	287.51	《China Energy Statistical Yearbook 2013》 [14]
Modified asphalt (3.5% SBS)	311.61	485.54	《China Energy Statistical Yearbook 2013》and Eurobitume [11] calculation
Emulsified asphalt (60% DPU)	118.55	205.98	《China Energy Statistical Yearbook 2013》and Eurobitume [11] calculation
Stone	3.71	9.02	Investigation
Comment	136	377.06	《China Energy Statistical Yearbook 2013》
Industrial water	0.0857	0.24	《Comprehensive Energy Consumption Calculation Principles 2008》 [15]
Steel	674	1868.67	《China Energy Statistical Yearbook 2013》
Asphalt heating	0.04	0.09	Investigation
Aggregate heating	10.9	24.2	Investigation
Asphalt mixture mixing	1.62	3.99	Investigation
Cement concrete mixing	4.09	8.93	Investigation

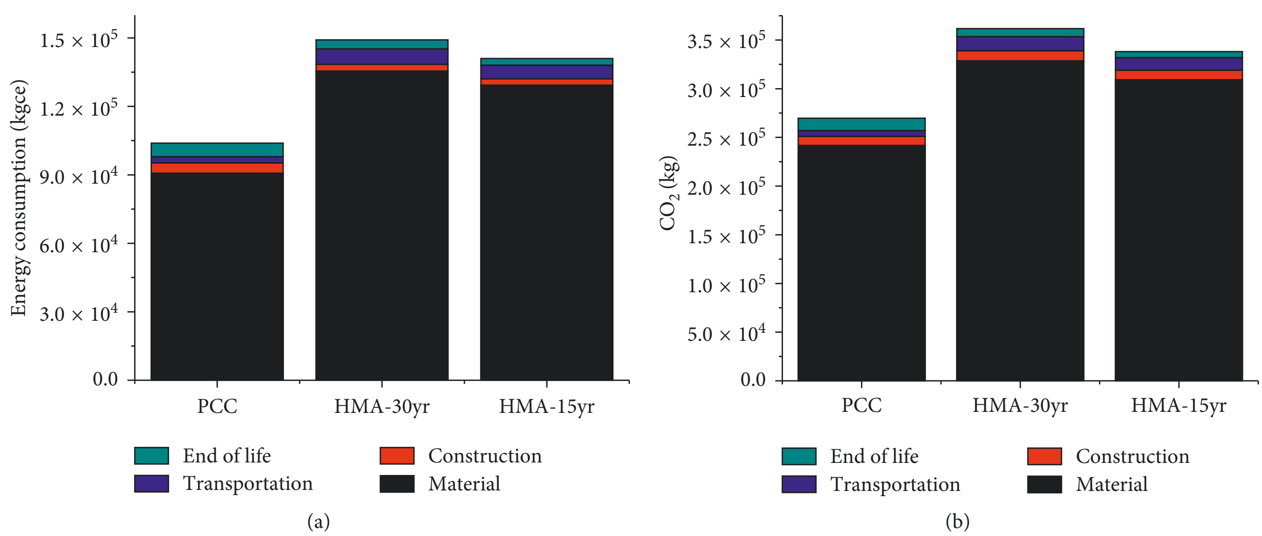

Figure 1: (a) Energy consumption and (b) CO_2 emission of the three pavement structures.

Table 5: Life-cycle inventories of the three pavement structures.

Cement			Asphalt (15 years of design)			Asphalt (30 years of design)		
Modules	Energy consumption (kgce)	CO_2 (kg)	Modules	Energy consumption (kgce)	CO_2 (kg)	Modules	Energy consumption (kgce)	CO_2 (kg)
Material production	90773	241737	Material production	129326	309219	Material production	135508	328646
Construction	4432	9416	Construction	2716	9887	Construction	2914	10373
Transport	2758	5859	Transport	6024	12799	Transport	6797	14443
Postprocessing	5958	12658	Postprocessing	2931	6228	Postprocessing	3908	8303

With the data in Table 5, the analysis chart can be drawn, shown in Figure 1.

mixing energy consumption are introduced, and the influence of those parameters on the LCA calculation results is needed to be examined. Those parameters and their fluctuation range are specified in Tables 6–7.

4.3.3. Results of LAC Model Uncertainty Analysis. The Monte Carlo analysis was performed based on the parameters inputted in Sections 4.3.1 and 4.3.2. After 50 times of iteration, the results are shown in Figure 3.

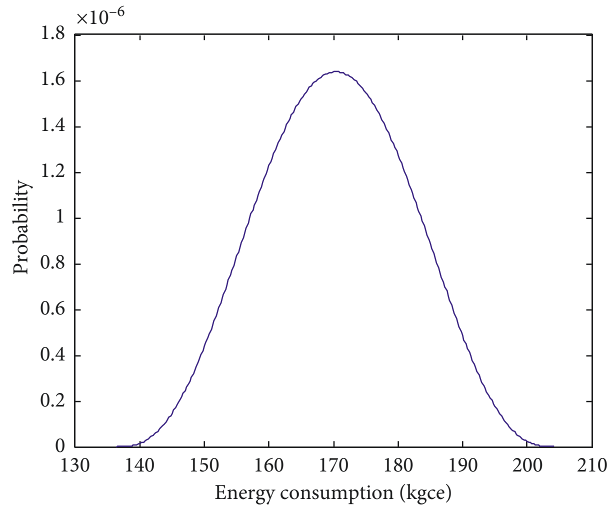

Figure 2: Probability density function of base asphalt production energy consumption.

Table 6: Parameter uncertainties of the asphalt pavement LCA model.

Stage	Parameters	Uncertainty[1]	Distribution form
Material production	Asphalt production	—	Probability density function
	Aggregate production	UF = 1.62	Lognormal distribution
	Mixing	UF = 1.47	Lognormal distribution
	SBS amount[2]	UF = 1.09	Uniform distribution
	Asphalt amount	UF = 1.09	Uniform distribution
	Asphalt aggregate heating	UF = 1.09	Uniform distribution
Construction stage	Shift	UF = 1.09	Uniform distribution
Transportation stage	Transport distance	UF = 1.41	Uniform distribution
	Carbon emission rate of transportation energy	UF = 1.14	Uniform distribution
Postprocessing stage	Shift	UF = 1.09	Uniform distribution
	Transport distance	UF = 1.41	Uniform distribution

Note. 1: uncertainty parameters determined by engineering investigation (the subscripts are similar); 2: the asphalt amount adjusted with SBS amount.

Table 7: Parameter uncertainties of the cement pavement LCA model.

Stage	Parameters	Uncertainty[1]	Distribution form
Material production	Cement production	—	Probability density function
	Aggregate production	UF = 1.62	Lognormal distribution
	Mixing	UF = 1.47	Lognormal distribution
	Cement amount	UF = 1.09	Uniform distribution
	Steel amount	UF = 1.09	Uniform distribution

Note. 1: uncertainty parameters in the remaining stages are consistent with those in Table 2.

In Figure 3, the left Figure 3(a) shows the average energy consumption and its standard deviation for different scenarios, and Figure 3(b) shows the probability density function for each scenario. From Figure 3(a), the energy consumption of the PCC scheme is smaller than the HMA scheme generally. It can be found that the coefficient of variation of the PCC program, 30-year, and 15-year design of the HMA program are 7.4%, 9.0%, and 9.1%, respectively, when it is used as the indicator of energy fluctuation range. The volatility of the PCC program is slightly less than HMA program. Since the maximum volatility of all programs is about 10%, which is quite limited, the energy consumption indicators of different programs have a good stability.

Define R as the ratio of the energy consumption of design 1 to the energy consumption of design 2, and then P (R<1) means the probability that R is less than 1. According to Figure 3(b), 50000 Monte Carlo analyses were performed, and the results are shown in Figure 4.

It can be seen from Figure 4 that the probability that the energy consumption of the cement pavement structure is less than the 15-year design asphalt pavement structure is 97%, and the probability that the energy

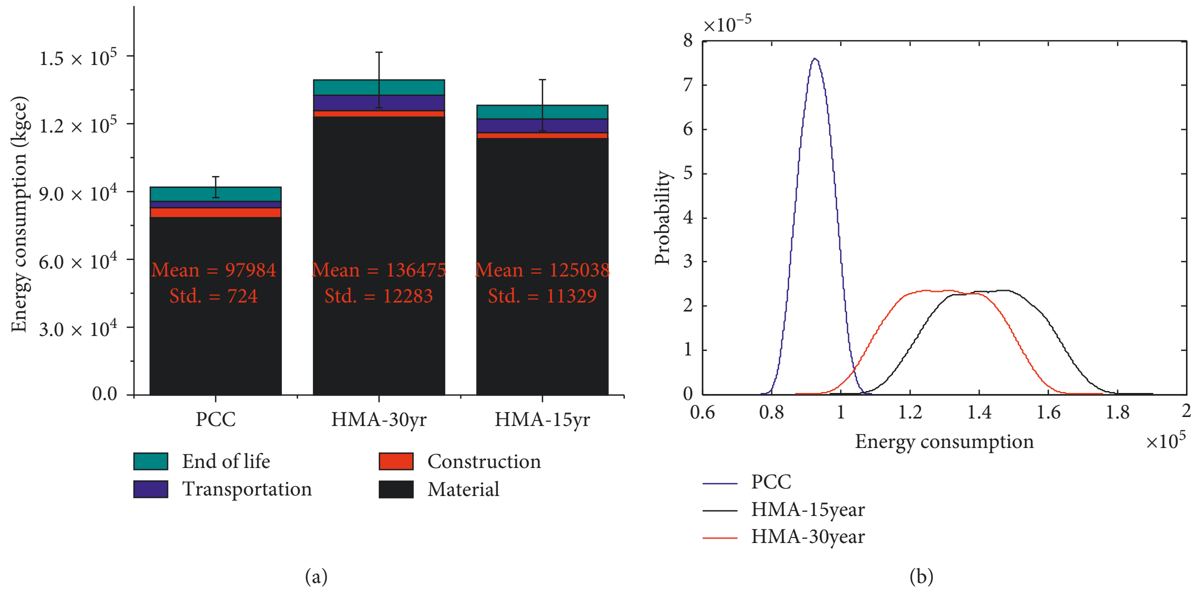

Figure 3: Energy consumption comparisons of the three pavement structures.

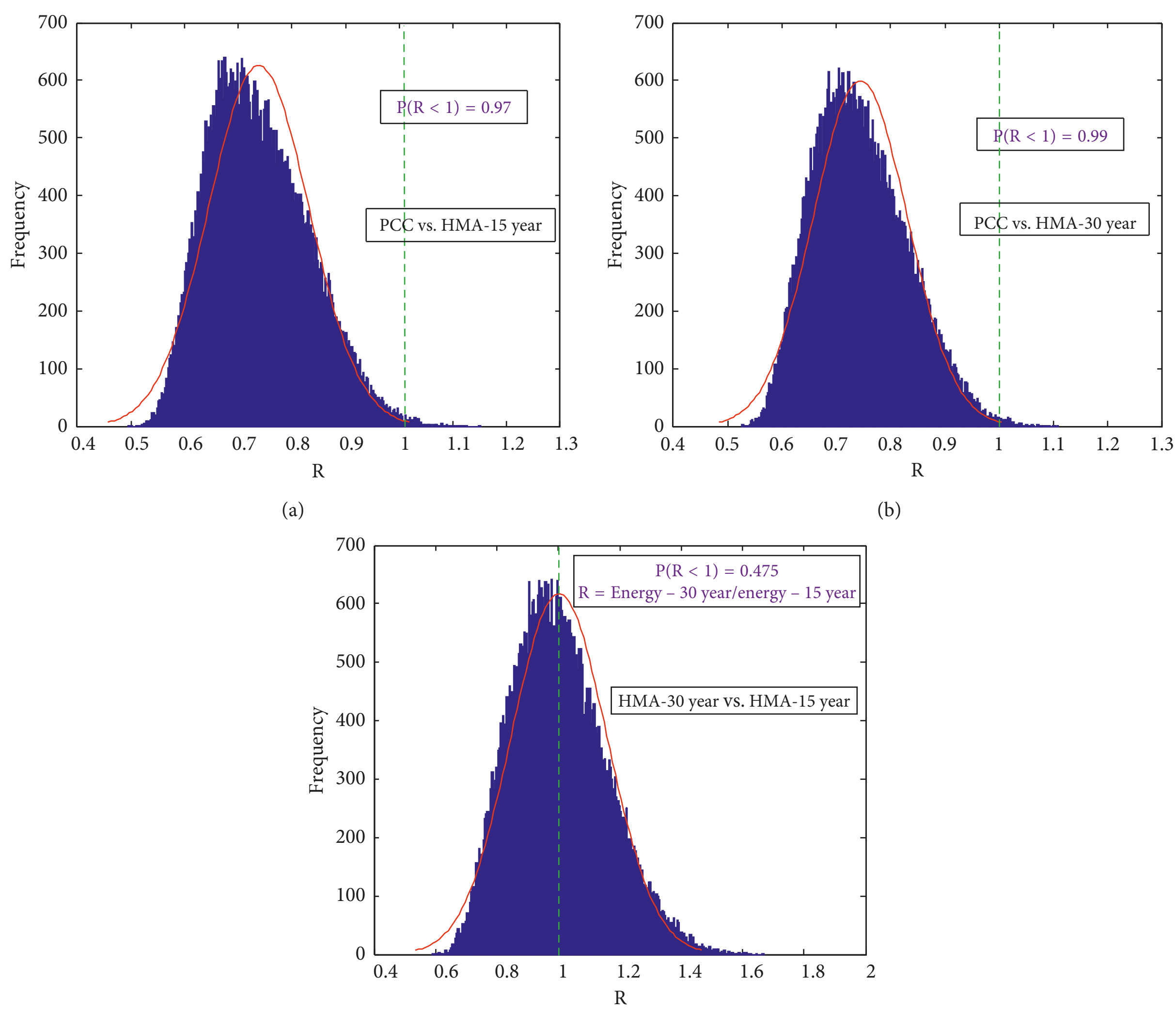

Figure 4: Energy consumption ratio probability distribution of the three pavement structures.

consumption of the cement pavement structure is less than the 30-year design asphalt pavement structure is 99%. Under the conditions set in this study, the cement pavement structure consumes less energy during the life cycle at the 95% confidence level. Comparing these two asphalt pavement designs, the probability that the energy consumption of the 30-year design asphalt pavement structure is less than that of the 15-year design asphalt pavement structure is 47.5%. It is difficult to have sufficient reason to detail the difference in environmental impact between the two structural designs. Similar conclusions can be drawn for carbon emissions indicators and will not be repeated here.

5. Conclusion

(1) A road LCA model with complete system boundary has been constructed. This model can not only describe the environmental impact of the road during service, but also can be used to assess the environmental impact of road materials in a measurable way.

(2) A rigorous method for evaluating the reliability of LCA model calculation results is constructed, which can be used to evaluate the reliability of LCA model settlement results under data quality and model assumptions.

(3) Under the established research background, the environmental impact of the cement pavement structure is less than the asphalt pavement structure at the 95% confidence level. The average energy consumption and carbon emission of the cement pavement is 21.6%–28.2% lower than the asphalt pavement during the life cycle.

(4) The reliability analysis shows that the results of the LCA model are stable and the fluctuation range is about 10%.

(5) Under the research background setup, there is no obvious environmental difference between the 15-year design life asphalt pavement and the 30-year design asphalt pavement at the 95% confidence level.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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