Chapter

Integrated Life Cycle Economic and Environmental Impact Assessment for Transportation Infrastructure: A Review

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Abstract

In order to realize the sustainable development of transportation infrastructure, more and more attention has been paid to the multi-scheme selection method of road engineering, while the existing life cycle cost analysis (LCCA) and life cycle assessment (LCA) methods are often isolated from each other, which cannot better realize the comprehensive evaluation of road life cycle. This chapter will review and summarize the development of LCCA and LCA systematically. Pointing out the existing problems in current research, the idea of integrated evaluation method combining LCA and LCCA is proposed. It puts forward the future development direction based on the deficiency of the current research results and provides useful reference for the popularization and application of the life cycle methods in road engineering.

Keywords: life cycle assessment, life cycle cost analysis, transportation infrastructure

1. Introduction

According to the definition of ISO 14040, life cycle refers to the continuous and interrelated stage of the product system, which generally starts from the acquisition of raw materials or products from natural resources and ends with the final treatment. It considers the planning, design, production, distribution, operation, use, maintenance, and recycling of the product, from the initial or design phase of the product, as shown in **Figure 1**.

Existing life cycle methods include life cycle cost analysis (LCCA) and life cycle assessment (LCA). Similar to the engineering budget method, the LCCA extends the time range of evaluation to the whole life of the product and focuses on its use, maintenance, and recycling, making the evaluation of the product more comprehensive and reasonable. With the increasing awareness of environmental protection, LCA, a method of evaluating product life cycle impact from the perspective of environmental impact rather than economic cost, has also been further developed. Now the application of LCA has become mature in many fields. In the early twenty-first century, the international road engineering research began to introduce LCA and developed a series of professional LCA analysis software. ISO 14040 points out

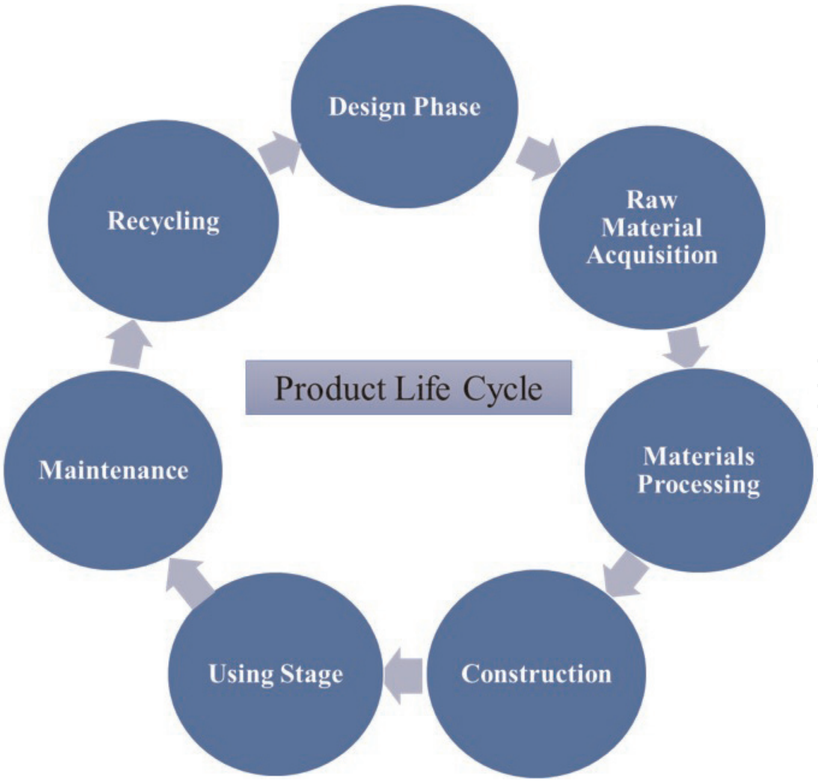


Figure 1.
Product life cycle.

that LCA method is composed of four parts: definition of goals and scope, inventory analysis, impact assessment, and result interpretation. It studies and analyzes the stages of raw material acquisition, construction, use, maintenance, and end of life, which is of great significance for promoting the ecological development of road construction. However, existing analysis isolates economic costs and environmental impacts from each other and fails to fully explore the overall impact of the product.

This chapter will summarize the international research development of LCCA and LCA applied on transportation infrastructure and puts forward the idea of evaluating the whole life cycle by combining the two life cycle methods; the calculation models involved in the integrated method will also be introduced, so as to provide reference for the decision of multi-scheme comparison in road engineering and the popularization and application of the life cycle methods.

2. Development of LCCA and LCA

2.1 Development of life cycle cost analysis

The concept of life cycle cost analysis (LCCA) has been introduced into the road engineering since the 1960s, when it was proposed by the US military and applied to the procurement of military equipment, aiming to solve the problem of deterioration of pavement performance and increase of maintenance costs at that time. The AASHTO pavement design guide of 1986, 1993, and 2002 all required the use of LCCA for the comparison and selection of the scheme, and the design specifications prepared by the National Highway Network in 1995 clearly stipulated that a complete LCCA report must be made for government investment projects exceeding $25 million [1].

Walls and Smith [31], issued a technical bulletin on LCCA, introducing a detailed method for calculating user costs in the operating area and introducing probabilistic methods to discuss the uncertainty of LCCA. The announcement first discusses the basic principles widely followed by LCCA and then gives the application case of traditional LCCA pavement design. Secondly, the uncertainty of input parameters is discussed, and the acceptable range of time and discount rate is provided. Thirdly, the sensitivity analysis of traditional LCCA method is discussed. Finally, it proposes the specific contents of user cost including delay cost, vehicle operation cost, and accident cost and presents the specific calculation method [2].

Delwar and Papagiannakis evaluated government and user costs of roads under a variety of road and traffic conditions, based on data from the Department of Transport in Washington. The evaluation results show that the user cost may be significantly higher than the government cost, so the user cost cannot be ignored in the life cycle cost analysis [3].

Chan et al. studied and analyzed the accuracy of LCCA decision-making and the accuracy of life cycle costs based on data and case studies from the Michigan Department of Transportation. The results show that LCCA can correctly predict and select the lower cost pavement scheme, but the actual cost is usually lower than the estimated value of LCCA. This result may be due to the inadequate consideration of specific pavement characteristics in cost estimation, so improving the process of pavement construction and maintenance cost estimation can help to realize the potential of LCCA pavement scheme selection [4].

To sum up, after 10 years of development, the analysis method of LCCA is relatively mature at present, but there is still a lack of data needed for evaluation. Since its inception, LCCA has been widely used in the road industry and has become a necessary component of road program evaluation in the United States. So far, the classification and calculation methods of owner cost and user cost of LCCA have been relatively mature, and the corresponding calculation tools have been widely used in many states of the United States [5].

2.2 Development of life cycle assessment

In the 1970s, the oil crisis caused widespread global interest in energy, and then the world began to see a boom in building energy consumption research. The energy consumption survey of buildings first emerged in the United States and the United Kingdom. They mainly inspect the energy consumption of existing buildings, tap their energy saving potential, and carry out energy saving transformation, which is called energy auditing [6]. Initially, researchers abroad concentrated on civil buildings and then gradually extend to all aspects of infrastructure construction. Research on road energy consumption has also appeared relatively early, and a lot of research achievements have been made and applied in practice.

Häkkinen and Mäke lä studied the life cycle of pavement in Finland based on the life cycle assessment theory. Through the analysis and comparison of common concrete pavement and stone matrix asphalt (SMA) pavement, the author thinks that in terms of energy consumption, if feedstock energy (refers to the combustion energy contained in raw materials of road construction, which can no longer be used as energy) is taken into consideration, asphalt pavement consumes twice as much energy as cement concrete pavement. If feedstock energy is not included, the energy consumption of these two pavements is equal. In terms of carbon dioxide emissions, common concrete pavement discharges 40–60% more than asphalt pavement, and the difference varies depending on the specific maintenance scheme [7].

Horvath and Hendrickson evaluated hot-mixed asphalt concrete pavement and continuously reinforced concrete pavement (CRCP) in the United States. After analysis and comparison, the author came to the conclusion that during the production stage of materials, the energy consumption of asphalt concrete pavement is about 40% more than that of CRCP, but most of the environmental indicators of asphalt concrete pavement are better than that of CRCP [8].

Roudebush compared and analyzed the cement concrete pavement and asphalt concrete pavement in the United States. The author concluded that the value of the asphalt pavement is approximately one time more than that of the cement pavement, about 90.8%. In the stage of material production and pavement maintenance, the energy value of asphalt concrete is approximately two times that of cement concrete [9]. Berthiaume and Bouchard applied exergy, an energy derivative, to study the energy consumption and environmental impact of asphalt and cement concrete pavement structure in Canada. Exergy describes the energy differences of thermodynamic equilibrium between products, which is a tool for measuring product energy and explaining energy quality differences [10].

Mroueh et al. got rid of the traditional comparison between asphalt and concrete and focused on the evaluation and analysis of the application of industrial by-products in pavement structure. The report analyzed the environmental impact of seven pavement structures with fly ash, crushed concrete waste, and blast furnace slag as the substitutes of original materials [11].

Stripple made a comparatively comprehensive study and comparison between cement concrete pavement and cold mix and hot mix asphalt concrete pavement, including accessory facilities of highway such as vegetation, fence, sign, and so on. According to the report, the energy consumption of cement concrete pavement is higher than that of asphalt concrete pavement. For the asphalt mixtures, they both produce the same amount of energy in the stage of production, but the cold mix one increases the energy consumption due to the addition of emulsifier [12].

Nisbet et al. listed life cycle inventory (LCI) of urban roads and highways in the United States and analyzed the energy consumption of cement concrete pavement and asphalt concrete pavement, respectively. For asphalt concrete pavement, the impact of transportation factors is not obvious. When the feedstock energy of asphalt is included, cement concrete pavement requires less materials, has lower energy resources, and has less exhaust emissions, no matter for urban roads or highways [13].

Park et al. based on the method of composite life cycle assessment, combined with the Korean economy and national energy balance sheet, applied the input–output model to assess energy consumption and gas emissions from roads in material selection and production stages [14].

Zapata and Gambatese [15] found that the results of Horvath and Hendrickson [8] were contrary to those of Stripple [12]. Therefore, by using the same preset conditions as Horvath and Hendrickson, the energy consumption of asphalt concrete pavement and continuous reinforced concrete pavement (CRCP) during the material production and construction stage is analyzed to make a relatively fair comparison. The results show that CRCP consumes more energy in the material production and construction stage, of which the energy consumption of cement production is the main factor, while the drying energy consumption of mixed aggregates is the significant factor affecting the energy consumption of asphalt pavement [15].

The framework of life cycle environmental assessment is relatively complete after years of research, but there are still a lot of deficiencies in the detailed model, and the data collection is also in the initial stage. The framework and theory of LCA have been accurately described in ISO 14040/ISO 14044 series standards, but there are still many different opinions and methods in its application on road.

3. Application of life cycle assessment in China

In China, research on road energy consumption is mainly carried out from a single aspect, such as production of raw materials or construction technics, but few research focus on the energy consumption during the lifetime of pavement.

From the perspective of economy and energy consumption, Fusen Fang studied and analyzed the cement pavement and asphalt pavement with a life span of 30 years in 1984. The author believes that when the discount rate is no more than 12%, the present value cost of cement concrete pavement is always less than asphalt concrete pavement. However, when the energy contained in asphalt itself is ignored, the energy consumption of cement concrete pavement is 8–17% more than that of the asphalt one [16].

Gu found that the less smooth the pavement, the higher the fuel consumption of the car. By studying the relationship between road surface smoothness and automobile fuel consumption, the author mainly discussed how to improve the pavement smoothness as a way to save energy and gain economic benefits [17].

Ye studied the fatigue and energy consumption optimization design of cement-stabilized base. The multilayer elastic system theory is used to directly calculate the stress and strain of pavement structure to obtain its mechanical and fatigue characteristics. Based on this, the paper performs thickness optimization and simple energy consumption analysis and calculation and discusses the technical, economic, and social benefits of cement-stabilized base [18].

Zhang started with the application effect of the old asphalt regenerator researched and produced in Guizhou province and collected relevant work efficiency quota data in the regenerated asphalt pavement project in Anshun, Duyun, and Zunyi. After comprehensive analysis and comparison, it is found that the energy consumption is different due to different seasons [19].

Han made an economic comparison between cement pavement and asphalt pavement in terms of construction cost and fuel consumption, mainly comparing the price of raw materials and the cost of maintenance, and thought that cement pavement has great advantages over asphalt pavement in economy. Moreover, from the perspective of pavement operation, the author analyzed that the fuel consumption of asphalt pavement is about 10% more than cement pavement due to the phenomenon of “deflection basin” of flexible structure of asphalt pavement [20].

Yi et al. compiled the energy consumption calculation and environmental assessment methods for the warm mix asphalt (WMA) and half-warm mix asphalt mixture. The analysis shows that the heating of coarse aggregate and the evaporation of water consume nearly 70% energy in the process of mixing. The production temperature has a great influence on the energy loss in the process of asphalt mixture mixing. The higher the production temperature, the more the energy loss. The energy loss during the mixing process of half-warm mixed asphalt mixture is nearly 50% less than that of hot mix asphalt mixture [21].

Shang et al. used the LCA theory and method to divide the life cycle of highways into four stages: material production, construction, maintenance, and dismantling, so as to study the energy consumption and atmospheric emissions within the life cycle of highways. According to the research, the proportion of energy consumption in the production stage of building materials is about 55.7% of the total energy consumption, followed by the maintenance and repair stage 40.5%, the construction stage 5.6%, and the dismantling stage 4%. The results show that most of the highway life cycle energy consumption is the direct and indirect energy consumption in the material production process [22].

Tang and Song summarize the low-energy warm mix asphalt concrete construction technology in the application of G109 national highway rebuilding project and, through the experiment monitoring, found that after the application of the technology, mixing, transporting, and paving of the mixture temperature were significantly reduced, saving energy consumption, reducing the CO_2 and smoke emissions, and effectively reducing the negative impact of the project which brings to the plateau fragile ecological environment [23]. Pan studied the life cycle energy consumption and carbon emission of highway. After modeling and quantitative analysis of energy consumption and greenhouse gas emissions in different stages of highway life cycle, the author thinks that the average annual energy consumption of cement concrete pavement is less than that of asphalt concrete pavement. Therefore, from the perspective of energy saving, cement concrete pavement is superior to asphalt concrete pavement [24]. Shi analyzed the energy consumption of asphalt pavement regeneration materials in road maintenance. After investigating the energy consumption of five different pavement materials in the four stages of raw material production, mixing plant, transportation, and construction machinery, it was found that the energy consumption of regenerative mixture is less. Therefore, from the perspective of energy saving, the regenerative technology is worth spreading [25].

Ma et al. evaluated the energy consumption of continuous reinforced concrete pavement and hot mix asphalt pavement in the construction process and made it clear that reducing the amount of early energy consumption in the production stage of raw materials in the pavement life cycle is conducive to promoting the sustainable development of the highway engineering field [26].

Li used LCA method to compare the environmental impact of continuous reinforced concrete pavement with asphalt pavement. The energy consumption and emission are quantitatively analyzed by selecting a reasonable calculation method for each stage. Among them, the calculation method of energy consumption includes quota method and IRI—speed—fuel consumption model. The results show that the green degree of continuous reinforced concrete pavement is higher than that of asphalt concrete pavement [27].

Zhang et al. analyzed the influence of different asphalt structural layer design parameters on the carbon emission characterization results. The results show that the greenhouse effect is the most serious in the construction period of asphalt pavement, accounting for more than 95%, and the carbon emissions in the production stage have the greatest impact on the greenhouse effect [28].

Due to the complexity of pavement system, problems still exist in the application of LCA in China:

- There are many differences in the assumptions of system boundary and boundary conditions.

- In the process of inventory analysis, the life stages considered in many studies are not comprehensive.

- Models and methods of life cycle assessment are not unified, lacking of consistent criteria for data analysis during the interpretation phase.

- Due to the opacity of domestic industry data, when the LCA method is applied in China, most of the list data are mostly directly from foreign literature or database, so its reliability is difficult to be guaranteed.

4. Existing problems in current research

There are relatively few studies on the integrated evaluation methods of life cycle economic cost and environmental impact. For the research in this field, the economic cost and environmental impact of multiple schemes are usually calculated separately, and then the advantages and disadvantages of the schemes are compared by multi-objective optimization. Shu et al. firstly analyzed the differences between the two life cycle methods and introduced the basic principles and disadvantages of PTLaser and TCAce, two software platforms that integrate the two in foreign countries, so as to provide references for domestic researchers [29]. Batouli et al. evaluated the life cycle costs and environmental impacts of different pavement design schemes, and the results showed that the initial cost of flexible pavement was lower, but it would bring higher long-term costs and environmental impacts [30]. Umer et al. proposed a road scheme evaluation system, integrating LCCA and LCA, and carried out a multi-objective analysis based on economic cost and environmental impact. It is proved that geosynthetics can be used to improve the service life of low-traffic road surface and to minimize the cost and environmental impact.

In general, the research on the comprehensive evaluation of economic cost and environmental impact within the life cycle in China is still in the stage of independent research, lacking the integration and comprehensive use of the two.

5. Life cycle economic and environmental impact assessment analysis

5.1 Life cycle cost analysis

RealCost, an LCCA software developed by the US federal highway administration, has been recognized and used in a number of states in the United States, becoming a widely recognized LCCA evaluation software. RealCost's LCCA method divides the life cycle cost into two parts, owner cost and user cost [31].

5.1.1 Owner cost

The owner cost is the cost borne by the operator of the pavement. In the range of life cycle, it includes the initial construction cost, maintenance cost, and pavement management cost. The economic costs associated with these processes are attributed to the owner's costs, which can be calculated by the budget method. It must be noted that the calculation range is the life cycle of the road, so it is necessary not only to calculate the economic cost of the whole process of construction acceptance but also to estimate the economic cost of daily maintenance, rehabilitation, and recycling after the road is put into use as well as the economic value in the end of the road life cycle. Here is a simple example of how this economic value is calculated:

Suppose that the life cycle economic cost of two different road schemes needs to be evaluated and the time range of evaluation is 30 years. If one of the roads just reaches its service life in the 30th year, then the second kind of residual value is 0. If one of the highways is reconstructed in year 28 and will remain in use until year 35 to reach its useful life, the size of the second type of remnant is.

$$(35\text{–}30)/(35\text{–}28) \times \text{the cost of the road rehabilitation} \tag{1}$$

5.1.2 User cost

User cost can be divided into three parts: vehicle operation cost, delay cost, and safety cost. Vehicle operation cost refers to the cost of vehicle operation near the maintenance operation area, and its size is affected by such factors as vehicle type, vehicle age, and the condition of maintenance operation area. Delay cost refers to the time delay cost caused by the maintenance operation area, whose main part is the person in the vehicle. Therefore, its size is not only affected by the nature of the construction operation area but also closely related to the time cost of the person. Safety cost refers to the cost of additional accidents caused by the presence of the maintenance operation area. The detailed calculation models will be mentioned in the following part of "Independent algorithm of LCCA."

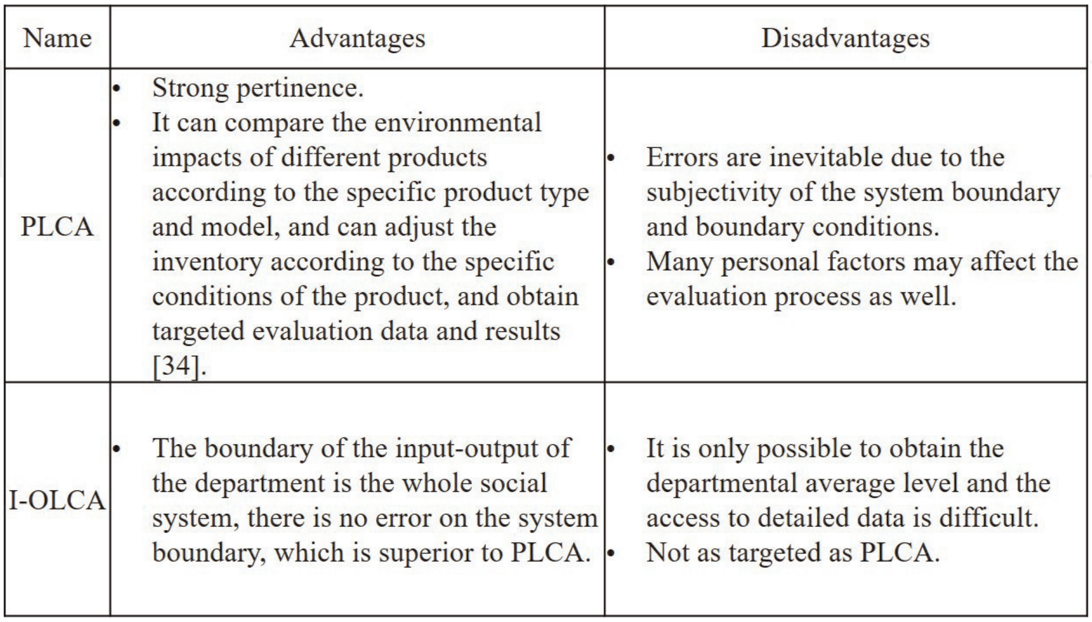
The existing evaluation method of the economic cost of life cycle is relatively complete, which mainly takes into account the construction and repair costs of the owner in the life cycle and the economic, time, and safety costs of the user in the construction process and converts them into a unified economic indicator through the discount rate.

5.2 Life cycle assessment analysis

The LCA method can be divided into three categories, namely, process-based LCA (PLCA), input–output LCA (I-OLCA), and hybrid LCA (hLCA) [32].

Process-based LCA (PLCA) is derived from the study of Coca-Cola bottles by the Midwest Institute of the United States in the late 1960s and is the earliest and most traditional method of life cycle assessment. The latest standard ISO 14040/ISO 14044 issued by the ISO in 2006 established the basic framework of LCA and proposed related requirements and guidelines [33]. It is an analytical method, mainly through investigation and literature review, collecting the input and output lists during the product life cycle.

Unlike PLCA, the input–output life cycle assessment (I-OLCA) is a method of pursuing an overall life cycle analysis. It first uses the input and output of the entire department to calculate the energy consumption and emission levels at the



Name	Advantages	Disadvantages
PLCA	• Strong pertinence. • It can compare the environmental impacts of different products according to the specific product type and model, and can adjust the inventory according to the specific conditions of the product, and obtain targeted evaluation data and results [34].	• Errors are inevitable due to the subjectivity of the system boundary and boundary conditions. • Many personal factors may affect the evaluation process as well.
I-OLCA	• The boundary of the input-output of the department is the whole social system, there is no error on the system boundary, which is superior to PLCA.	• It is only possible to obtain the departmental average level and the access to detailed data is difficult. • Not as targeted as PLCA.

Table 1.
Comparison of LCA methods.

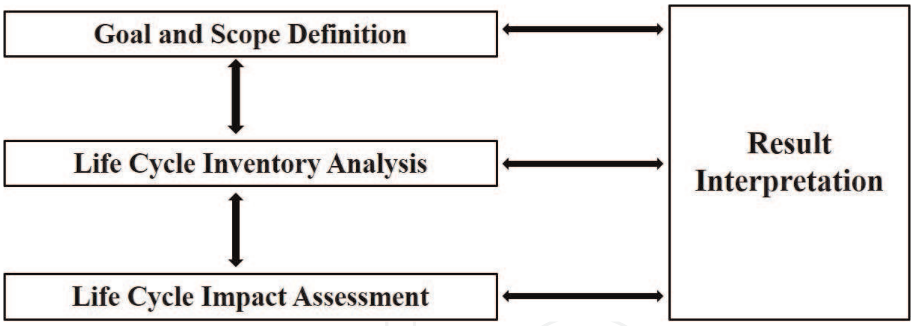


Figure 2.
Procedure of PLCA. These four steps are interrelated and interacting. For example, the problems discovered during the interpretation phase can be returned to the impact assessment, inventory analysis, and even the goal and scope determination steps to be corrected [34].

department level and then evaluates the environmental impact of specific products through the corresponding relationship between the evaluation target and the economic sector. The advantages and disadvantages of each method are shown in **Table 1**.

Hybrid LCA (HLCA) is the combination of the above two methods for evaluation, which makes it possible to eliminate the error caused by the system boundary and enhance the pertinence of the evaluation object, so it is more widely used. However, due to the complexity of the road system, its input and output are both diversified and recessive. Therefore, the existing road life cycle assessment is mainly based on PLCA. If not explained in detail, all life cycle assessment methods in this chapter refer to the PLCA.

The life cycle assessment method can be divided into four steps according to the ISO standard: determining the goal and scope, inventory analysis, impact assessment, and result interpretation, as shown in **Figure 2**.

6. Integrated life cycle economic and environmental impact method

As mentioned above, the calculation process of life cycle cost analysis is to divide the total cost into two categories according to the undertaker, owner cost and user cost, and further subdivide and calculate these two types of costs. The road life cycle inventory analysis process, in order of time and space, calculates the environmental impact of the whole life cycle; however, further discussion of each part will find a lot of similarities between the objects evaluated by the two as shown in **Figure 3**.

For example, the “raw material acquisition” and “construction” stage in LCI and the “construction” part in LCCA are evaluated on the pavement materials and construction process. The “maintenance” stage in LCI includes both the “maintenance” and “management” processes in LCCA. It refers to the maintenance work performed by the owner to maintain its structure and function after the pavement is put into use. It also contains the user’s cost of evaluation, which is the additional cost and impact of the maintenance of the user. Therefore, there is a great deal of consistency between LCI and LCCA in the process of evaluation, which is also because both of them take pavement as the evaluation object. There are overlaps between the two methods. Many calculations are done by budget method. Both of them are the selection methods of multi-plan comparison, highlighting the differences of multi-plan while downplaying or ignoring the evaluation of the similarities of multi-plan. The biggest difference between the two lies in the different evaluation objectives: LCCA aims at the economic cost, while LCI aims at the environmental impact.

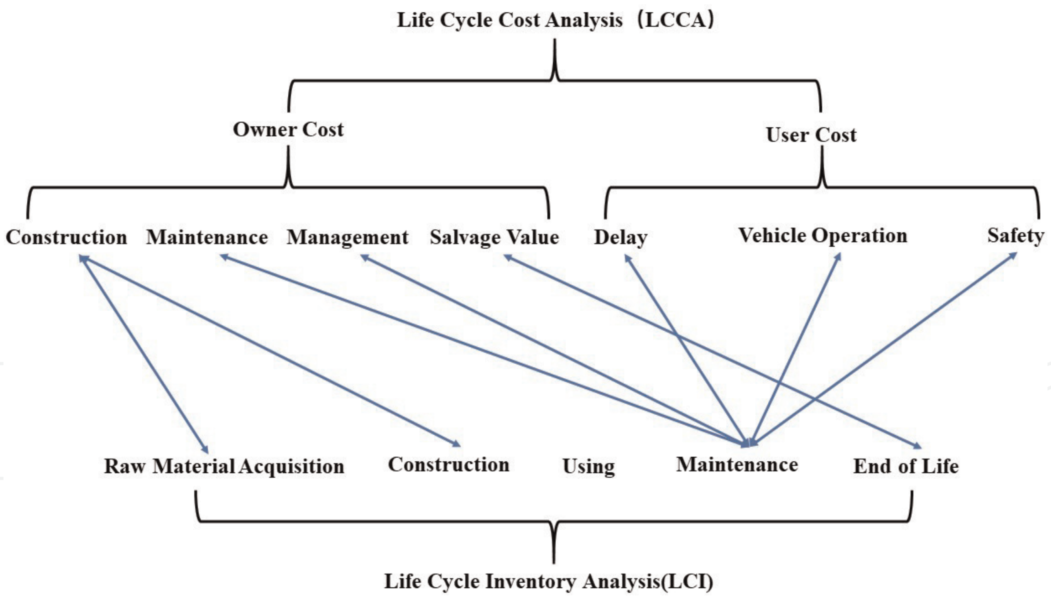


Figure 3.
Differences and similarities between LCA and LCCA.

Since LCCA and LCI have a lot of similarities between the process and the framework, it is possible to take both LCCA and LCI into account. Compared with LCCA's classification method based on undertaking subject, LCI's spatiotemporal sequence is relatively easier to understand and operate, and LCA's framework is also more extensive and logical. Therefore, it is possible to integrate LCCA's evaluation goals into the process of LCI to realize synchronous analysis of economic cost and environmental impact.

6.1 Goal and scope

The research goal that should be identified includes the cause of the research, the intended use of the research results, the intended users, and publicity; the scope of the study to be determined includes the research object and its functional units, system boundaries, boundary conditions, impact assessment methods and categories, interpretation methods, assumptions, limitations, and other various research elements. The research objectives vary according to the collective situation of the evaluation, while the research scope such as functional units and system boundaries have their commonalities.

6.2 Inventory analysis

The inventory analysis step is to make statistics and calculations of the environmental impacts in each stage of the pavement life cycle, including data collection and data calculation.

Due to the complexity and protracted nature of the pavement system, this process is generally divided into several stages. The common practice divides the whole life of the pavement into five stages: raw material acquisition stage, construction stage, using stage, maintenance stage, and end of life, as shown in **Figure 4**.

6.2.1 Raw material acquisition stage

The inventory analysis of the raw material acquisition stage mainly calculates the environmental impact of all pavement material production processes before

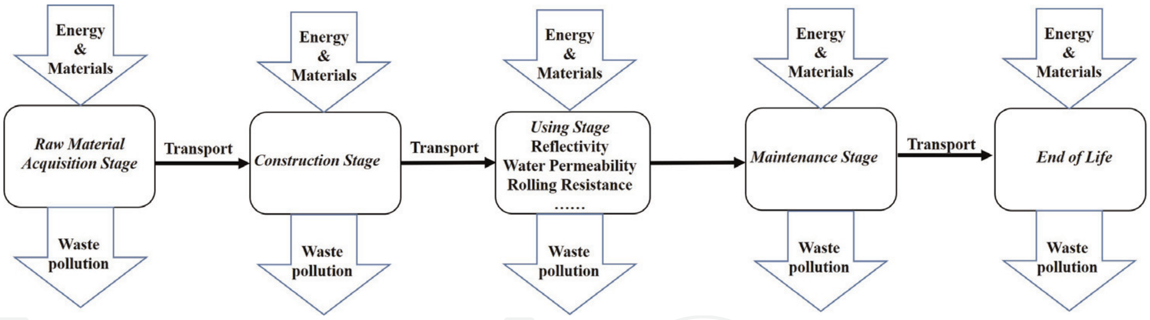


Figure 4.
General pavement life cycle.

construction. This process includes not only the environmental impact of the production process of materials such as asphalt, cement, and aggregates but also the transportation and mixing processes of these materials [35]. The environmental impact calculation method at this stage is similar to the budget estimate. The overall environmental impact is calculated via the product of the amount of material and equipment used and the environmental impact per unit amount. The environmental impact per unit can be determined by the product of energy consumption per unit and the environmental impact of energy combustion per unit.

Taking carbon emissions as an example, if there are **n** species of energy and **m(i)** types of material or equipment that consume the **i**th energy, the total carbon emissions can be calculated using Eq. (2) along with Eq. (3). Other kinds of impacts can be calculated in a similar way:

$$\text{Total carbon emissions} = \sum_{i=1}^{n} \text{Energy consumption}(\mathrm{i}) \times \text{Carbon emissionsper unit} \tag{2}$$

$$\begin{aligned}\text{Energy consumption}(\mathrm{i}) = \sum_{j=1}^{\mathrm{m(i)}} &\text{Materials or equipments consumption}(j)\\ &\times \text{ Energy consumption per unit}\end{aligned} \tag{3}$$

The production process of some materials is relatively complicated, and the environmental impact per unit is difficult to obtain quickly. For example, asphalt as a petrochemical product is one of the many products in the petrochemical industry. Environmental impacts need to be further counted and distributed to each product, and its production process varies with region and time, making it difficult to obtain an accurate value [36]. Therefore, the collection of these data is difficult to achieve through individual behavior, and it requires the efforts of governments and organizations.

Countries such as Europe and the United States have been working on this aspect earlier and have obtained a lot of relatively reliable data. In developed countries, work in this area is mostly carried out and supervised by industry associations such as asphalt associations and concrete associations, and they, respectively, investigate and collect environmental impacts of products in their industry [37]. It is worth noting that the data collection and environmental impact assessment methods coordinated by industry associations are not necessarily input–output LCA methods. In fact, they use PLCA more.

6.2.2 Construction stage

This stage mainly calculates the environmental impacts of pavement leveling, spreading, and rolling. In addition, the transportation of raw materials from the place of origin to the mixing plant and transportation from the mixing plant to the construction site are all related to this stage and can also be classified into this stage. The environmental impact calculation method at this stage is similar to the raw material acquisition stage. The overall environmental impact is calculated via the product of the amount of material and equipment used and the environmental impact per unit amount. The specific energy consumption can be calculated according to the one-shift quota and one-shift consumption of the construction code [38] and can also be analogized according to the actual situation of similar projects.

6.2.3 Using stage

This stage mainly calculates the environmental impact caused by the interaction of the pavement surface with vehicles and the environment. It is the most complex phase of the pavement life cycle and the most imperfect stage so far. The pavement system as part of the entire transportation system, its performance, and behavior will have an impact on the environmental burden of vehicles and the environment [39]. For these impacts, many researchers have studied the specific influence modes and relationships from various aspects, among which the research on road rolling resistance and reflectivity is especially numerous. The following mainly introduce the environmental impact model of the pavement surface from two aspects of rolling resistance and reflectivity.

6.2.3.1 Rolling resistance impact model

The rolling resistance of the pavement is the main factor affecting the vehicle consuming during the interaction between people and vehicles. There are now many models for assessing the impacts of rolling resistance on vehicle fuel consumption, which can be divided into four categories depending on whether rolling resistance changes and vehicle speed changes are considered. The more factors are included, the higher the model's simulation of the real situation and the more complex the relative model. Commonly used models include the HDM-4 model issued by the World Bank [40] that considers variable rolling resistance and constant speed and MOVES model for variable rolling resistance and vehicle speed released by the US Environmental Protection Agency [41].

Wang of the University of California Pavement Research Center (UCPRC) proposed a comprehensive rolling resistance environmental impact assessment method in 2012 [39–42]. Based on Wang's research on rolling resistance [36],

$$F_{rolling} = CR_2 \times FCLIM \times \left(b_{11} \times N_w + CR_1 \times \left(b_{12} \times M + b_{13} \times v^2\right)\right) \tag{4}$$

where $F_{rolling}$ is the rolling resistance (N); CR_1 is tire type parameter; CR_2 is pavement characteristic parameter related to international roughness index (IRI), mean texture depth (MPD), and deflection value; $FCLIM$ is the climatic factor; N_w is the total number of tires; b_{11}, b_{12}, and b_{13} are parameters about tire type and technique; M is the vehicle quality; and v refers to vehicle speed (m/s).

Then use the MOVES model to calculate the relationship between rolling resistance and fuel consumption [35]:

$$\begin{aligned}\text{VSP} &= \text{Rolling resistance} + \text{Air resistance} + \text{Inertial and Gradient resistance}\\ &= F_{rolling} \times \frac{v}{M} + F_{Aerodynamic} \times \frac{v}{M} + F_{\text{Inertial and Gradient}} \times \frac{v}{M}\\ &= C_R \mathrm{g} \times v + \frac{1}{2}\frac{\rho_a C_D A_{front}}{M}(v+v_w)^2 \times v + (a(1+\varepsilon_i) + \mathrm{g} \times grade) \times v\\ &= \frac{A}{M} \times v + \frac{B}{M} \times v^2 + \frac{C}{M} \times + (a(1+\varepsilon_i) + g \times grade) \times v\end{aligned} \tag{5}$$

where VSP is vehicle-specific power that refers to vehicle power per unit mass (W/kg), $F_{Aerodynamic}$ is air resistance (N); $F_{\text{Inertial and Gradient}}$ is inertia or gradient resistance (N); C_R is rolling resistance coefficient; ρ_a is ambient air density (1.207 kg/m^3, 20°C); v is vehicle speed (m/s); v_w is vehicle upwind speed (m/s); A_{front} is vehicle windward area (m^2); C_D is air resistance coefficient; ε_i is the quality factor, its value equal to the equivalent translation quality of rotating components (wheel, gear shaft, etc.) in the transmission system; *grade* is the gradient which is the vertical rise divided by slope length; g is acceleration of gravity (m^2/s); M is vehicle quality (kg); a is vehicle acceleration (m^2/s); A is the rolling resistance coefficient in the MOVES model; B is the high rolling resistance and rotational loss coefficient in the MOVES model; and C is the air resistance coefficient in the MOVES model.

The specific power of a vehicle can be used to measure the power required to operate a vehicle under different conditions, and together with the speed of the vehicle determines the state and fuel consumption of the vehicle engine. The MOVES model simulates the operating state of each vehicle in a certain time range by calculating the specific power and speed of the vehicle running every second, and then sums the time and the number of vehicles according to the state and fuel consumption of different vehicles, finally obtain the overall fuel consumption of the vehicle in a certain time and space.

The MOVES model uses a simulation method to calculate the fuel consumption of a large number of vehicles which is relatively accurate and meticulous, but there are also many problems in its local application. First of all, due to the existence of a large number of environmental impact assessment method, this section adopts a simplified calculation method for the influence of rolling resistance on fuel consumption, which is easy to operate:

First, according to Wang, the linear relationship between vehicle fuel consumption and IRI is introduced in Eqs. (6) and (7):

$$\begin{aligned}&\text{Additional fuel consumption of gasoline vehicle} = (\text{IRI–Initial IRI}) \times 0.0313 \times \text{Length}\\ &\times \text{Standard fuel consumption of gasoline vehicle} \times \text{Traffic volume} \times \text{Length of the road}\end{aligned} \tag{6}$$

$$\begin{aligned}&\text{Additional fuel consumption of diesel vehicle v} = (\text{IRI–Initial IRI}) \times 0.00739 \times \text{Length}\\ &\times \text{Standard fuel consumption of diesel vehicle} \times \text{Traffic volume} \times \text{Length of the road}\end{aligned} \tag{7}$$

Then, according to the IRI decay formula and maintenance formula, the continuous pavement parameters in a certain time can be obtained:

$$\sqrt{IRI} = -0.174 + 9.66 \times 10^{-5} \times \sqrt{CumulativeESAL} + 1.15 \times \sqrt{InitialIRI} \tag{8}$$

$$IRI \text{ change} = -0.6839 + 0.6197 \times \text{Initial } IRI \tag{9}$$

where IRI refers to the international roughness index of the pavement at any time (m/km), cumulative ESAL refers to the cumulative axle load frequency after maintenance, and Initial IRI is initial international roughness index after road maintenance.

6.2.3.2 Reflectivity impact model

The reflectivity of the pavement refers to the reflection ratio of the road surface to solar radiation. The reflectivity of the pavement affects the surrounding environment in various ways, thereby generating economic cost and environmental impact.

Lawrence Laboratories in the United States released their reflectivity model in 2017. It takes urban building energy consumption as the evaluation object and evaluates the environmental impact of reflectivity from a city perspective [43]. Increasing the reflectivity of the pavement reduces the amount of heat absorbed by the pavement and increases the amount of heat that is reflected to the surrounding buildings. The former reduces the average temperature of the city and alleviates the urban heat island effect; the latter increases the temperature of nearby buildings, increases cooling costs, and reduces heating costs. In general, the former has a greater utility than the latter, so a highly reflective pavement can effectively alleviate the urban heat island effect. There are also many studies that assess the environmental impact of road reflectivity from a more macro perspective, considering the effect of reflectivity on radiative forcing. Radiative forcing is a measure of the extent to which a factor affects the earth-atmosphere system's energy ingress and egress energy balance. It is also an index that reflects the importance of this factor in the underlying climate change mechanism. There are many ways to calculate radiative forcing, and the simplest one can be calculated using Eq. (10) [44]:

$$\Delta m_{CO_2} = 100 \times C \times A \times \Delta\alpha \tag{10}$$

where Δm_{CO_2} is the amount of change in CO_2 emissions; C is a constant of CO_2 emissions, using 255 kg/m^2 as the reference value; A is pavement area; and $\Delta\alpha$ is the variation of pavement reflectivity. This model considers only the effect of reflectivity changes on CO_2 emissions, so it is the simplification model without considering time and environment.

In addition, there is another method for calculating the radiative forcing considering time variation, as shown in Eq. (11) [45]:

$$+0.01\alpha = \frac{1.087 \times RF \times t}{0.217 \times t - 44.78e^{-t/172.9} - 6.26e^{-t/18.51} - 0.22e^{-t/1.186} + 51.26}[kgCO_2] \tag{11}$$

The left side of this formula indicates a change in the reflectance per unit area of 0.01, and the right side indicates the CO_2 emissions caused by the change in reflectance over time t. RF refers to the change in radiative forcing due to changes in surface reflectance, with a reference value of 1.12–2.14 W/m^2. Because this method is relatively simple, it does not need to consider the localization of multiple parameters. It has been used by many studies and indirectly proves that it has certain reliability.

6.2.3.3 Impact from other factors

In addition to the above factors, cement and asphalt binders will also undergo changes in properties under environmental influences, which will have an impact on the environment. During the firing of cement, limestone releases a large amount of CO_2. With the long-term use of cement pavement, the limestone in the pavement will reabsorb the CO_2 in the air. This process gradually reduces the concentration of CO_2 in the air and forms a negative carbon emission value. However, since the speed of absorbing CO_2 is difficult to determine, this process may take several years or maybe decades or centuries [46]. In the long-term use of asphalt pavement, there will be surface runoff on the densely paved road surface, and there will be permeate water on the permeable pavement, which will bring the asphalt precipitate in the asphalt mixture into the water source. However, many studies have shown that it is unlikely that pollutants in the asphalt pavement will reach dangerous concentrations [47].

6.2.4 Maintenance stage

This stage mainly calculates the environmental impact of various maintenance strategies during the long-term use of the pavement. The main environmental impacts at this stage are divided into direct and indirect effects. Direct impacts include the environmental impacts of material production and maintenance construction required for maintenance activities, which are similar to the material production and construction phases. Indirect impact refers to traffic delays caused by maintenance activities, which creates an additional environmental burden. The maintenance of the pavement must partially or completely block traffic for a period of time, causing the vehicle to slow down or bypass, which will result in an increase in fuel consumption of the vehicle.

6.2.5 End of life

This stage mainly calculates the environmental impact caused by different treatment methods at the end of the life of the pavement. The main disposal methods are classified into two categories: burying and recycling [48].

The disposal method of burying is to crush the pavement material and bury it. The environmental impact of this process is divided into three parts, namely, the consumption of crushing, transportation, and burying. There is little literature on the environmental burden of materials after burying, and further research is needed.

Recycling is to break up the pavement material and use it as aggregate to be added to the new pavement material in a certain proportion. In actual engineering, there are various methods for recycling, which can be divided into thermal regeneration and cold regeneration depending on the regeneration temperature and can also be divided into on-site regeneration and in-plant regeneration according to the regeneration site. Since the recycled material comes from the old pavement system and is used in the new pavement system, how the environmental benefits brought by the circulation are distributed between the two systems is a problem still being studied and discussed. The existing distribution methods include cutoff, loss of quality, closed loop, equalization (50/50), and substitution [44]. But there is still no way to get consistent recognition. Due to the lack of data, the equalization method is the most commonly used method. Although it ignores the quantity and importance of recycled materials, it has the best maneuverability in practice [49].

6.3 Independent algorithm of LCCA

6.3.1 Labor costs and direct monetary inputs

There will be a large amount of labor input in the process of road construction, maintenance, and recycling. At the same time, some direct monetary input as indirect fee is inevitable. The economic costs of these inputs are relatively easy to calculate, but their environmental costs are difficult to measure directly, so they are calculated as independent economic costs, regardless of their synchronous environmental costs. In the actual calculation, these costs will be directly incorporated into the total economic costs of the corresponding stage.

6.3.2 User cost in the maintenance stage

As mentioned in the analysis of LCCA, user cost can be divided into three parts: vehicle operation cost, delay cost, and safety cost [2]. Vehicle operation cost refers to the cost of vehicle operation near the maintenance operation area, and its value is affected by vehicle type, vehicle age, condition of maintenance operation area, and other factors. The calculation formula of vehicle delay cost in the maintenance area is as Eq. (12), where the vehicle operation cost (/km·vehicle) is a value that changes with areas and time:

$$\begin{aligned}\text{Vehicle delay cost} = {} & \text{Length of operation area} \times \text{AADT} \times \text{Duration of operation} \\ & \times \text{Vehicle operation cost}\end{aligned} \tag{12}$$

Delay cost refers to the time delay cost caused by the maintenance operation area; it is not only affected by the construction operation area but also closely related to the time cost of people. The calculation of delay cost is shown from Eqs. (13) to (16). The time value is determined by the average income level and working hours:

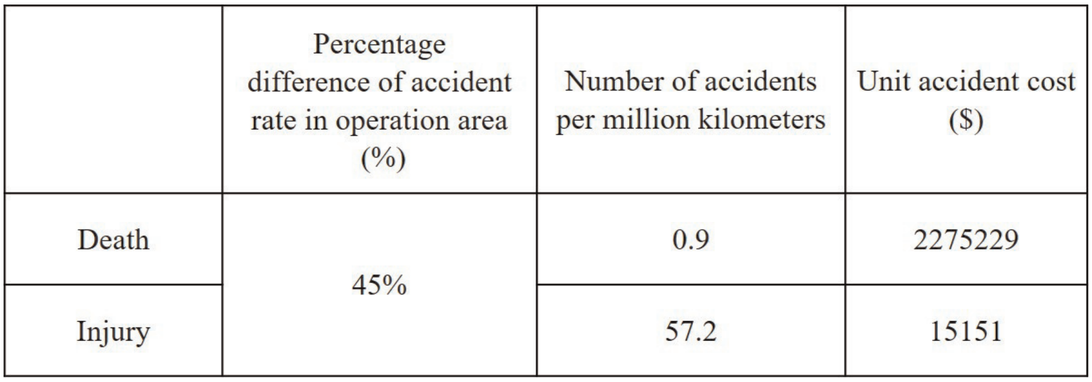
$$\begin{aligned}\text{Deceleration delay time} = {} & (\text{Length of operation area}/\text{Speed of operation area}) \\ & - (\text{Length of operation area}/\text{Upstream driving speed})\end{aligned} \tag{13}$$

$$\text{Queue time} = \text{Queue length}/\text{Queue speed} \tag{14}$$

$$\text{Total delay time} = \text{Deceleration delay time} + \text{Queuing time} \tag{15}$$

$$\text{Delay cost} = \text{Total delay time} \times \text{AADT} \times \text{Working time} \times \text{Time value} \tag{16}$$

Safety cost refers to the cost caused by additional accidents due to the existence of maintenance operation area. The specific calculation method is shown in Eqs. (17) to (20). The parameters refer to the values in **Table 2**:



	Percentage difference of accident rate in operation area (%)	Number of accidents per million kilometers	Unit accident cost ($)
Death	45%	0.9	2275229
Injury		57.2	15151

Table 2.
The value of safety cost parameter.

$$\text{Vehicle mileage} = \text{Number of daily trips} \times \text{Days} \times \text{Mileage} \tag{17}$$

$$\text{Number of accidents} = \text{Number of accidents per km} \times \text{Vehicle mileage} \tag{18}$$

$$\begin{aligned}&\text{Number of accidents caused by operation area} = \text{Number of accidents}\\&\times \text{Percentage difference of accident rate in operation area}\end{aligned} \tag{19}$$

$$\text{Safety cost} = \text{Number of accidents caused by operation area} \times \text{unit accident cost} \tag{20}$$

6.3.3 Economic cost discount rate

When discussing the costs generated in the future, the expected costs and benefits in the future need to be converted into present value, which is called net present value (NPV). Due to the uncertainty in the future, the conversion of future benefits and costs into present value will show the trend of depreciation, and the degree of depreciation depends on the economic and social environment, represented by the discount rate. Since the life cycle cost analysis of the road only considers the cost expenditure, the calculation formula of its NPV is as follows [2, 3]:

$$\begin{aligned}\text{NPV cost} = \text{Initial construction cost} \sum_{k=1}^{N} \text{k th Future expected cost}\\ \left[\frac{1}{(1+\text{Discount Rate})^{\text{years expected}}}\right]\end{aligned} \tag{21}$$

6.4 Impact assessment

So as to use the results of the inventory analysis for decision-making, the results of the inventory analysis must be collated and compared to illustrate the equivalent value and importance of each specific environmental impact category. This evaluation process can be divided into four steps: classification, distribution, characterization, and quantification.

6.4.1 Classification

Classification is to put the result of the inventory analysis into different environmental impact categories. This phase requires the selection of appropriate classification methods and models to distinguish different impact categories. The current classification is to divide environmental impact into three categories: resource consumption, natural environment, and human health, with subgroups of abiotic resource use, acidification, climate change, eco-toxicity, eutrophication, human toxicity, land use, particulate matter formation, photochemical ozone formation, stratospheric ozone depletion, water use, etc. [50].

6.4.2 Assignment

The assignment assigns the results of the inventory analysis to each category to determine the impact category for each of the output substances. Many pollutants can be classified into the same category. For example, nitrogen oxides (NO_x) and sulfur oxides (SO_x) can be classified into acidification, and carbon dioxide (CO_2) and methane (CH_4) can be classified as climate change, as shown in **Figure 5**.

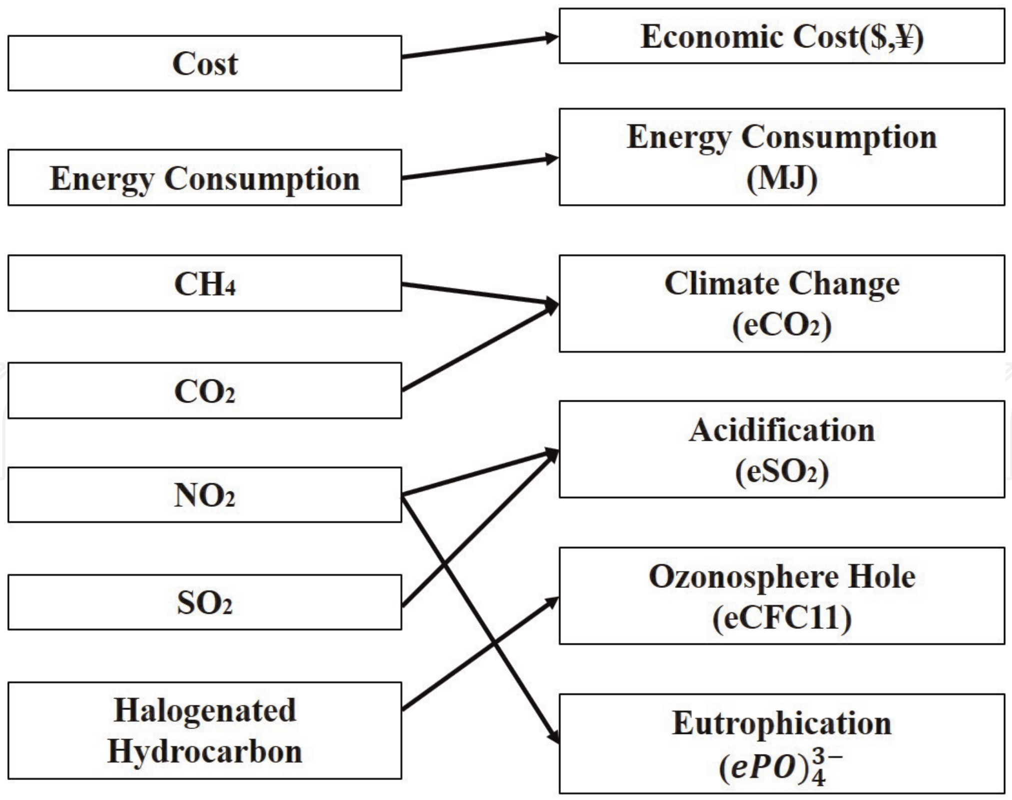


Figure 5.
Classification, assignment, and characterization.

6.4.3 Characterization

The process of characterization is to attribute different pollutants in the same category to the same indicator. For example, climate change includes not only carbon dioxide (CO_2) and methane (CH_4) but also hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), etc. Through the results of natural science research, the global warming capacity of various greenhouse gases over a certain period of time (generally 100 years) is compared with carbon dioxide, thereby converting them into a certain amount of equivalent carbon dioxide, and summing up, the equivalent carbon dioxide emission (CO_2e) is used to evaluate the global warming potential [51]. This convert is to multiply greenhouse gas emissions by a parameter that characterizes global warming to get equivalent CO_2 emissions, and this parameter is called impact factors (IF). For other environmental impact categories, of course, there are corresponding evaluation indicators and impact factors.

Some commonly used characteristic units are given in **Figure 5**, such as evaluating acidification potential by equivalent sulfur dioxide emissions and ozone hole potential by equivalent Freon emissions. It is noteworthy that the characteristic unit is not exclusive, some models evaluate the acidification threat by equivalent nitrogen dioxide emissions, and there are corresponding pollutant impact factors which are different from those used in equivalent sulfur dioxide emissions. This is also unmistakable and feasible, and this is the biggest difference between LCA impact assessment models.

6.4.4 Quantification

The process of quantification is the process of data processing of the equivalent indicators of each category. There are two common methods for this process: normalization methods and standardized methods. These two methods are essentially a linear transformation that transforms the data into more easily understood values and improves the expressiveness of the evaluation results. The difference between the two is that normalization will classify the evaluation results into the interval [0, 1] and the standardized results are related to the overall distribution of the data. This stage is an optional stage in the impact assessment, and the results of the evaluation vary depending on the evaluator and the evaluation method.

6.5 Result interpretation

6.5.1 Data uncertainty analysis

When various uncontrollable external factors change, the evaluation plan and conclusion may be affected; this evaluation method is called uncertainty analysis, which is a commonly used method in decision analysis. Through this analysis, the impact of uncertainty factors on the evaluation results can be clarified and minimized, and the resistance of the evaluation conclusions to certain unforeseen risks can be predicted, thereby verifying the reliability and stability of the scheme.

Knowledge, experience, information, and judgment of future decision-making are required in uncertainty analysis. The commonly used methods are: (1) The profit and loss value of the scheme, that is, to calculate the different benefits caused by various factors, and the scheme with the largest return is the optimal scheme. (2) The regret value of the calculation scheme. Calculate the difference between the return value and the maximum return value of the scheme adopted due to the misjudgment of uncertain factors, and the scheme with the smallest regret value is the best scheme. (3) The expected value. By using probability to calculate the standard value of the scheme comparison, the scheme with the best expected value is the best scheme. (4) Consider the criteria of decision-making without deviating from the rules [52]. To sum it up, uncertainty analysis can be divided into break-even analysis, sensitivity analysis, probability analysis, and criteria analysis.

7. Conclusions

This chapter proposes a comprehensive evaluation idea of pavement life cycle economic cost and environmental impact based on the life cycle assessment framework, which is essentially equivalent to the environmental impact assessment method considering economic cost. The advantage of this method is that it considers both the economic cost and the environmental impact of the road and puts them in a unified framework for discussion and comparison. The results of comparison can be given more quickly and clearly in multiple schemes than in the selection, which is helpful for decision-makers to make choices.

Although LCCA and LCA have a large number of overlapped parts, some parts are independent of each other. For example, for the labor input of a certain project, economic inputs such as compensation and insurance must be considered, and it is difficult to quantify the environmental impact of labor input. It would therefore be inappropriate to consider only its economic costs and ignore its environmental impact. Therefore, it is suggested that a more comprehensive LCA system should include and is not limited to:

- Environmental aspects: factors such as global warming, human toxicity, resource depletion, ozone depletion, and eco-toxicity

- Economic aspects: factors such as owner costs and user costs

- Social aspects: factors such as worker income, accident rate, worker social welfare, and social disparity (industry, income, etc.)

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