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Eco-Cost Analysis of Split Air-Conditioner Using Activity-Based Costing Method

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ABSTRACT Split air conditioner (SAC) plays a critical role for temperature control of buildings. In recent years, the manufacturing process of SAC tends to consider energy-saving and environmental protection factors to reduce air pollution and alleviate energy crisis. However, the design of environmental-friendly SAC will increase the manufacturing cost, thereby increasing the burden on air-conditioning companies. Therefore, the eco-cost analysis of SAC is of great significance for air conditioner manufacturers. To this end, a new SAC eco-cost assessment method based on activity based costing method is innovatively proposed in this paper. In this method, a K-nearest neighbor algorithm is used to deal with the missing data in SAC samples. An environmental and non-environmental cost assessment approach is developed based on the activity-based costing method to estimate the eco-cost of SAC over its whole life cycle. In addition, the impact of energy efficiency deviation on SAC eco-cost is numerically analyzed. Finally, the proposed eco-cost assessment method is programmed on a Gabi software, and validated using real SAC data from a Chinese air-conditioning company. Simulation results show that the proposed method can provide an estimate of the eco-cost of SAC, thus helping air-conditioning companies to improve their competitiveness in the future where energy-saving and emission reduction are increasingly important.

INDEX TERMS Eco-cost analysis, split air conditioner, life cycle assessment, activity-based costing method, Gabi software.

I. INTRODUCTION

A. MOTIVATION

Split air conditioner (SAC) is composed of an indoor unit and an outdoor unit, which are connected to each other by pipes and wires [1]. It has been widely-used in buildings to provide comfortable environment for occupants due to its small space, low noise, flexible installation location, etc. Although SAC indeed improves the living environment of human beings, it will have a considerable negative impact on world environmental pollution and energy consumption [2]. On the one hand, the use of air conditioners consumes a lot of electricity, and 66% of the world's electricity comes from fossil fuels, which will exacerbate the natural greenhouse effect of the earth [3]. On the other hand, the manufacturing of SAC will emit harmful gases and discard solid waste, making the environmental pollution even worse [4]. With the increasing attention to environmental pollution and energy crisis over the world, the manufacturing process of SAC needs to consider energy-saving and emission-reduction. Nevertheless, the design of high-efficient SACs will increase its manufacturing cost, thereby increasing the burden on air conditioning enterprises. Therefore, how to simultaneously minimize the impact of SACs on nature environment and reduce the manufacturing cost is an urgent problem required to be resolved. The first step in solving this problem is to quantitatively estimate the ecological cost (eco-cost) of SAC. This paper aims to fill this gap.

SAC eco-cost is a measure that expresses the environmental burden of SAC on the basis of preventing that burden. In addition to the traditional cost of design, manufacturing, sale, and transportation, SAC eco-cost also needs to consider the costs with respect to environment, maintenance and recycling [5], etc. Apparently, SAC eco-cost analysis is extremely complex. Life cycle assessment (LCA) based traditional analysis methods may inevitably have truncation errors or require complex matrix calculation, making them improper for the eco-cost analysis of SAC [6]. Therefore, this paper proposes a

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new SAC eco-cost evaluation framework based on an activity-based costing method.

B. RELATED WORK

Activity-based costing (ABC) is a method that allocates indirect costs to products and services based on mathematical statistics [7]. In ABC method, it is assumed that cost consumes activity, and activity consumes resource. Here, activity refers to an event, unit of work, or a specific task. There are two types of activities in ABC: transaction driver and duration driver [8]. The former involves counting the number of times the activity occurs, while the latter measures how long it takes for the activity to complete. Practically, ABC method supposes that the total cost of a product consists of its direct cost and indirect cost, which not only broadens the scope of cost calculation but also improves the accuracy for cost accounting [9]. Therefore, ABC method is popular for cost accounting in manufacturing enterprises.

Durán *et al.* adopted fuzzy logic to model the variables in wastewater recovery, and proposed a hybrid costing method based on ABC [10]. A comparative study of traditional ABC methods and time-driven ABC method was given in [11]. The results showed that time-driven ABC is more accurate than traditional ABC methods when the traceability of resource to activity is relatively high. A new cost accounting method for emergency medicine was proposed based on ABC to determine which interventions can enhance the value of patients [12]. The construction cost of hydraulic engineering was theoretically analyzed, and the ABC method was employed to build its accounting model [13]. A logistics cost accounting model combining the basic model of logistics cost and ABC method was proposed to provide an effective basis for the decision-making of logistics enterprises [14]. An extensive review of ABC and work decomposition methods for analyzing offshore operating cost category was provided in [15]. A case study of time-driven ABC method for keeping the library's activities, resources and costs under control was presented in [16].

Traditional cost and eco-cost are different because [17]: (1) Eco-cost pays more attention to environment and resource-related costs, such as nature pollution; (2) Eco-cost assessment covers a long period of time, including the entire life cycle of SAC; (3) Eco-cost analysis involves multiple research fields such as energy, environmental protection and chemistry. In recent years, eco-cost analysis has received widespread concerns. For example, an eco-cost calculation method for electricity was proposed by taking into account environmental pollution, ecological damage and resource depletion [18]. The eco-cost analysis of a building was carried out in [19], considering energy efficiency cost, water recycling cost, indoor environmental quality cost, and raw material cost. Based on the theory of value-at-risk, the eco-cost of material scarcity was evaluated and a new method to solve the short-term material supply shortage problem was proposed [20]. An eco-efficient value creation method based on LCA was proposed to simultaneously reduce the eco-burden of a product and enhance the customer perceived value [21]. However, to the best of our knowledge, the eco-cost analysis of SAC has not yet been reported and fully investigated.

C. CONTRIBUTION

In order to fill this gap, this paper proposes a new SAC eco-cost assessment method based on ABC. Compared with the existing literature with similar topics, the contributions of this study are threefold:

- We propose a new eco-cost assessment method based on ABC to evaluate the environmental and non-environmental cost of fixed-frequency SAC (FFSAC) and variable-frequency SAC (VFSAC). In this method, activities over the entire life cycle of SAC are first analyzed and the resultant waste and emissions are classified. The impacts of wastes and emissions on environment are then numerically estimated, thus obtaining the eco-cost of SAC. To the best of our knowledge, this paper is the first attempt to evaluate the eco-cost of SACs.
- We propose a new method based on a K-nearest neighbor (KNN) algorithm to deal with the problem of missing data in the data collection process. This method can effectively fill in the missing data of SAC components, thereby making it possible to realize the eco-cost analysis of SACs.
- The proposed eco-cost assessment method based on ABC is comprehensively validated on a Gabi software using real SAC data collected from an air-conditioning company in China. The obtained results show that the proposed method can provide theoretical support and guidance when designing energy-saving and environmental protection-related policies.

The remainder of this study is organized as follows. Section II briefly summarizes the background of SAC, including ABC method, life cycle assessment and basic components of SAC. These backgrounds are used in Section III for SAC eco-cost analysis. Section IV proves the feasibility and effectiveness of the proposed method, and Section V presents the conclusions obtained in this study according to the simulation results.

II. BACKGROUND OF SAC ECO-COST ANALYSIS

This Section presents the backgrounds of SAC eco-cost analysis, including ABC method, life cycle assessment, and SAC components.

A. ACTIVITY-BASED COSTING METHOD

SAC eco-cost analysis is a complex process in which the environmental and non-environmental costs over the whole life cycle of SACs should be estimated. Traditional cost evaluation methods only take into account direct costs, without considering the indirect costs, so their evaluation results may have large deviations. Therefore, this paper proposes a new evaluation method based on ABC to improve the accuracy of the eco-cost analysis of SACs. Both direct costs and indirect costs are considered in the proposed method.

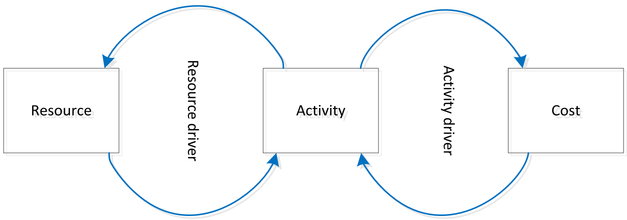

FIGURE 1. **The relationship of resource, activity and cost driver.**

ABC is a hybrid method combining process life cycle assessment (PLCA) and economic input-output life cycle assessment (EIOLCA). It has three elements, i.e., resource, activity and cost driver. As the source of cost, resource is basic element for producing an SAC. The manpower and materials consumed during the design process, and equipment and electricity consumed during the manufacturing process belong to resources. Activity refers to the resource-consuming behaviors carried out during the whole life cycle of the SACs, including product design, procurement, manufacturing and maintenance. Each link and each process can be regarded as an activity. The activity is the smallest unit for analyzing the eco-cost. Cost driver is the factor that causes the cost to occur. The cost drivers are usually measured by the resources consumed by the activity, such as the number of quality checks and the amount of power usage. The cost driver can be divided into resource driver and activity driver. The relationship among resource, activity and cost driver is shown in Fig. 1.

B. LIFE CYCLE ASSESSMENT

LCA is generally used to evaluate the energy consumption and environmental impact of a product, covering the stages from design and manufacturing to maintenance and recycling [22]. LCA was proposed in the early 1970s. Up to date, LCA method has been used in evaluation of various industrial products and engineering projects such as natural resource extraction [23]. Basically, LCA methods can be divided into PLCA, EIOLCA and hybrid life cycle assessment (HLCA) [24]. PLCA is the most traditional and classic LCA method. It belongs to a bottom-up analysis method that takes an input-output material list, energy and environmental emissions as the input variables. The advantage of the PLCA method is its ability to accurately analyze the impact of a product/project over its entire life cycle on the nature environment [25]. The disadvantage of PLCA is that it inevitably has a truncation error, that is, the accounting process is incomplete [26].

EIOLCA belongs to a top-down LCA method based on input-output tables [27]. The accounting boundary of EIOLCA is the entire national economic system. Therefore, EIOLCA can fully calculate the energy consumption and the environmental impact of products or engineering projects [28]. However, EIOLCA method generally exhibits departmental aggregation error because its evaluation results only reflect the average level of the department of the whole Nation. Another main drawback of EIOLCA is that it does not actually reflect the state of the art in current products/equipment [29]. This is because this method has time lag and the input-output table is updated every few years.

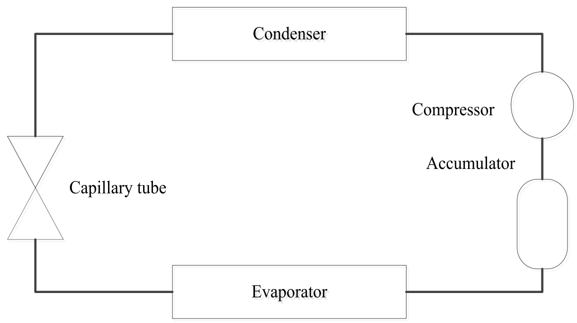

FIGURE 2. **Schematic diagram of a split air-conditioner.**

HLCA is a combination of PLCA and EIOLCA. The process life cycle part of the hybrid approach is represented by a technical matrix that considers the material and energy consumed in each process [30]. The input-output table of HLCA is the same as that of EIOLCA. The advantage of HLCA is that it can eliminate the truncation error, and can also incorporate the usage and recycling stages into the evaluation scope [31], [32]. However, HLCA is still in its infancy stage for practical application because it has high requirements for matrix calculations.

C. BASIC COMPONENTS OF SAC

To evaluate the eco-cost of SAC, we first need to analyze its basic components. In reality, a SAC is mainly composed of an evaporator, a compressor, a condenser and a capillary [33], as shown in Fig.2. The evaporator uses a liquid cryogenic refrigerant to evaporate at a low pressure as it absorbs the heat of the cooling medium to achieve the purpose of refrigeration. The compressor is intended to compress and drive the refrigerant through the air conditioning circuit. The compressor draws refrigerant from the low-pressure zone and compresses it into a high-pressure zone for cooling and condensation. The condenser is a heat exchanger and is a key component of the refrigeration system. It converts the refrigerant from vapor to liquid by quickly transferring heat from the pipe to the air near the pipe. A capillary connects the condenser and the evaporator to reduce the pressure of the liquefied refrigerant from the compressor.

SAC is a very complex household appliance and contains lots of components. To analyze its eco-cost, a list of all the components of a SAC should be collected [34], as shown in Table 1.

III. SAC ECO-COST ANALYSIS BASED ON ABC METHOD

This paper proposes a new method for analyzing the eco-cost of SACs. In this method, we first need to collect the component data of many SACs during their whole life cycles. Nevertheless, the component data may be missing in the data collection process. We therefore use a KNN algorithm to deal

TABLE 1. List of the components in a SAC.

No.	Components	No.	Components
1	Left side panel	2	Filter
3	Left drive box	4	Motor
5	Crankshaft	6	Baffle
7	Anti-mouse panel	8	Bearing seat
9	Bottom shell	10	Fan bearing
11	Drain pipe	12	Evaporator bracket
13	Evaporator	14	Flap
15	Wall panel	16	Brushless DC motor
17	Connecting pipe	18	Electrical box
19	Motherboard	20	Shielding cover
21	Right drive box	22	Baffle board
23	Rubber cord	24	Power cable
25	Remote controller	26	Antibacterial filters
27	Temperature-sensitive pipe	28	Compressor and its accessories
29	Clapboard	30	Cover
31	Chassis	32	Grille
33	Valve bracket	34	Shut-off valve
35	Right side panel	36	Four-way valve
37	Capillary	38	Condenser
39	Fixed bracket	40	Pipe clamp
41	Electric reactor	42	Top cover

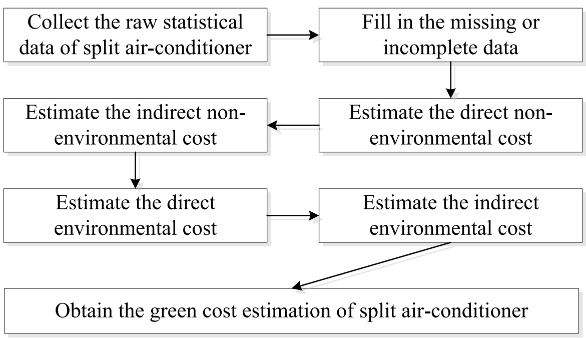

FIGURE 3. Evaluation process of the proposed SAC eco-cost analysis.

with the missing data. Next, an energy resource pool and an activity cost library of SACs are established based on ABC method. Then, a detailed list of environmental pollutants generated over the entire life cycles of SACs is obtained based on the LCA method. Finally, the life cost assessment method is adopted to transform environmental pollutants into environmental and non-environmental costs, and the eco-cost of an SAC over its whole life cycle can be obtained. The diagram of the proposed method is shown in Fig. 3. We now elaborate on the flowchart and key steps of the proposed eco-cost analysis method in the following subsections.

A. FLOWCHART OF THE PROPOSED ECO-COST ANALYSIS

This study proposes a new eco-cost assessment method for SACs using the ABC method. In this method, we first need to determine the estimation goals and scope of SAC eco-cost assessment. We then clarify the background, the relevant constraints and the boundaries of the external environment for eco-cost analysis. Subsequently, we determine the specific cost structure of the eco-cost of the SAC, that is, the type of costing activities and their corresponding hierarchy structure.

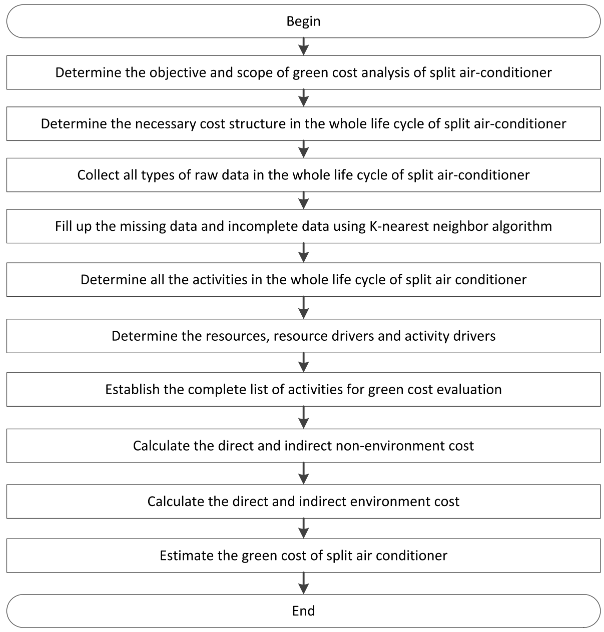

FIGURE 4. The flowchart of the proposed eco-cost analysis method.

A large amount of raw data, including supply chain data in the entire life cycle of SACs, standards, environmental laws and regulations, are collected.

We then use the K-nearest neighbor algorithm to deal with the missing data in the data collection process. Next, three basic elements of the raw data, namely activities, cost drivers and resources, are determined based on the activity-based costing method. The activities are abstracted from all the cost calculation processes involved throughout the entire life cycle of the SAC. Based on the activity list, the environmental and non-environmental costs of the SAC can be calculated. Finally, the non-environmental cost of the SAC plus the environmental cost is the eco-cost of the SAC. The flowchart of eco-cost assessment of SAC is shown in Fig. 4.

B. FILLING UP THE MISSING DATA

In order to estimate the eco-cost of SAC, it is required to collect many SAC samples, each of which contains the basic components in Table 1. However, we found that there are some component data missing in the data collection process. Three reasons account for the missing of the data: (1) some components are already missing in the air conditioner recycled; (2) some of the data are obviously wrong, and so we deal with them as the missing data; (3) human factor. Therefore, we develop a method to handle the missing data based on KNN.

KNN algorithm was first proposed by Cover and Hart [35] and Lin *et al.* [36]. Its principle is to calculate the similarity between a sample x to be classified and all other samples, and then find the K most similar samples according to the similarity. Then, the most frequently occurring sample among the K samples are taken as prediction value of the sample x.

The main steps of the proposed method are described as follows:

1) We observe the material data of each SAC, dividing the SACs without missing data into one category and the SACs with missing data into another category. We take the data of the former category as the training dataset, expressed as Ω, $\Omega = \{x_1, x_2, \ldots, x_n\}$, where $x_i = (x_i^1, x_i^2, \ldots, x_i^m)$. Here, n is the number of samples, and m is the number of elements in each sample.

2) In general, we need to initialize K and then adjust it according to the test results of the experiment on SAC. Here, K is set to a value of 3.

3) The distance between samples is generally measured by the Euclidean distance. We assume that the samples that are required to be filled up are denoted as Φ, $\Phi = \{y_1, y_2, \ldots, y_p\}$, where $y_i = (y_i^1, y_i^2, \ldots, y_i^m)$, and p is the number of the samples in Φ. In addition, y_i^j represents the j-th material of the i-th sample of the SAC. Consequently, we can calculate the Euclidean distance between any sample in Ω and any sample in Φ. For example, the distance between the j-th sample in Ω and the i-th sample in Φ can be expressed as:

$$d\left(x_i, y_j\right) = \sqrt{\sum_{h=1}^{m} \left(x_i^h - y_j^h\right)} \tag{1}$$

where $d(x_i, y_j)$ represents the distance between x_i and y_j. It should be noted that the distance is calculated without considering the missing data.

4) For each sample in Φ, we find the K nearest samples in Ω without considering the missing data. These K samples are represented as $x_1, x_2, \ldots, x_k$. Then the missing data can be statistically estimated by:

$$y_i^j = k_1 x_1^j + k_2 x_2^j + \ldots + k_K x_k^j \tag{2}$$

where y_i^j represents the j-th missing data in the i-th sample; k_K denotes the K-th weight; x_k^j stands for the j-th element of the k-th sample in Ω. Note that each missing data should be filled independently.

The above steps describe the entire process of the proposed algorithm based on KNN to deal with the missing data.

C. NON-ENVIRONMENTAL COST ESTIMATION BASED ON ABC

The eco-cost estimation of SACs involves the assessment of non-environmental and environmental costs. Non-environmental cost refer to the cost coming from various types of activities in the whole life cycle of SACs. It can be divided into five parts according to its activities in the whole life cycle, that is, the costs in research and development (R&D), manufacturing, sale, usage and recycling. R&D activities include marketing research, feasibility analysis, product design and sample testing. Manufacturing activities include assembly line design, component assembly, logistics management and product testing. Sale activities include the promotion, packaging, transportation and installation of SACs, as well as customer management. Usage activities include repair, maintenance and use. Recycling activities include disassembly, cleaning and testing of SACs. These activities in the whole life cycle of SAC will undoubtedly consume a lot of resources, including manpower, the components in Table 1, water and electricity.

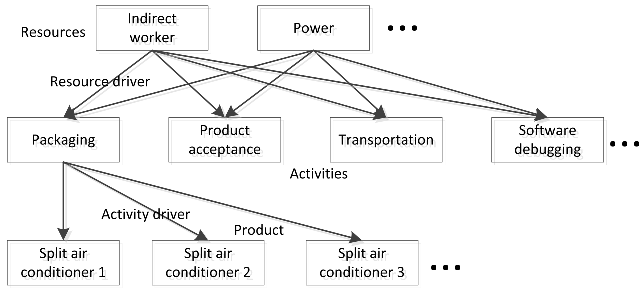

FIGURE 5. The method for calculating SAC indirect cost.

Non-environmental costs can be further divided into non-environmental direct costs and non-environmental indirect costs. The non-environmental direct costs can be calculated by means of the multiplication of the unit price and its corresponding quantity. For example, direct labor cost, direct material cost and some fixed costs can be calculated as follows:

$$C_w = \sum_{i=1}^{S} s_i \times h_i \tag{3}$$

$$C_m = \sum_{i=1}^{M} u_i \times q_i \tag{4}$$

$$C_f = \sum_{i=1}^{F} f_i \tag{5}$$

where C_w, C_m, and C_f represent the direct labor cost, direct material cost and fixed cost of the SAC, respectively; s_i, u_i and f_i are the hourly wage, material unit price and a fixed cost with S, M and F representing their respective numbers of cost items; h_i and q_i are the working hours and the quantity of materials, respectively.

The calculation of non-environmental indirect cost of SACs requires the allocation of indirect costs based on cost drivers, such as software cost, transportation cost, acceptance cost, and packaging cost. The principle of indirect cost calculation is given in Fig. 5. As shown, it can be seen that an indirect cost can be estimated as follows:

$$C_i^{id} = C_i^{av} \times q_i \tag{6}$$

where C_i^{id} is the indirect cost of the i-th item; q_i is the number of cost drivers; C_i^{av} represents the average cost of the i-th indirect cost driver, which can be estimated by:

$$C_i^{av} = C_i^{total} \Big/ N_i \tag{7}$$

where C_i^{total} is the total cost caused by all drivers, with N_i representing its quantity.

We explain the calculation process of non-environmental indirect costs by using transportation cost and acceptance cost, as follows:

$$C_{tr}^{id} = q_{tr} \times C_{tr}^{total} \Big/ N_{tr} \tag{8}$$

$$C_{ac}^{id} = q_{ac} \times C_{ac}^{total} \Big/ N_{ac} \tag{9}$$

where the subscripts tr and ac represent the transportation indirect cost and acceptance indirect cost, respectively.

It should be noted that the cost of SAC during the use stage mainly comes from the power consumption. Basically, power consumption also belongs to a kind of direct cost. And so the annual power consumption of SACs needs to be estimated in advance. Here, according to a large quantity of measured statistical data, this paper proposes a method for estimating the annual power consumption of SACs, as follows:

$$E_a = \frac{Q_c}{SEER_{on}} + H_{TO} \cdot P_{TO} + H_{SB} \cdot P_{SB} + H_{CK} \cdot P_{CK} + H_{OFF} \cdot P_{OFF} \tag{10}$$

where H_{TO}, H_{SB}, H_{CK} and H_{OFF} represent the annual hours of four operation modes, i.e., temperature adjustment device shutdown mode, standby mode, compressor crankcase heating mode and shutdown mode; P_{TO}, P_{SB}, P_{CK} and P_{OFF} are their corresponding power consumptions; $SEER_{on}$ is the seasonal operation energy efficiency ratio; Q_c is the reference annual cooling capacity, which can be estimated by:

$$Q_c = P_{de} \times H_{ce} \tag{11}$$

where P_{de} is the full-load power consumption of a SAC; H_{ce} stands for the reference annual hours for cooling and is set to 3672 hours.

D. ENVIRONMENTAL COST ESTIMATION BASED ON ABC

The environmental cost of SAC refers to the cost related to the environmental pollution and ecological damage of SAC during its whole life cycle. In the R&D process, environmental costs mainly include environmental-friendly design and the cost for improving the energy efficiency. The environmental cost in the manufacturing stage of SAC is mainly applied to address the exhaust gas and sewage, thus reducing the impact of these pollutants on the environment. In the sale stage, the environmental costs are mainly caused by environmental-friendly packaging and procurement processes. The environmental cost in the use phase is mainly the indirect cost of emissions generated by the power consumption. Finally, the environmental cost of the recycling phase is mainly the cost for recycling the waste. The above process for generating environmental costs is termed as the activities in the ABC method. Similarly, the environmental cost of the SAC can also be divided into the direct environmental cost and the indirect environmental cost. The direct environment cost is calculated in the same way as the direct non-environmental cost, as shown in Eqs. (3)–(5). We now elaborate on the method for calculating the indirect environmental cost based on EIOLCA.

We first divide the indirect environmental cost at each life cycle stage of SAC into many basic unit processors. A basic unit processor consists of two parts, input and output, as shown in Fig. 6. The inputs of the processor include materials, energy, and so on. Its output includes various

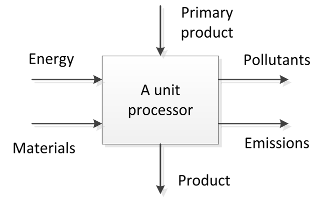

FIGURE 6. The unit processor for evaluating the indirect environmental cost.

environmental pollutants, exhaust emissions and products. Then, the list of environmental pollution factors in the whole life cycle of the SAC can be obtained by summarizing the input and output lists of each processor and collecting them in a layer by layer manner. Subsequently, we analyze the characterization factor in the obtained list according to the standard LCA method. Characterization is the process for converting a given type of pollutions and emissions into a single pollutant. For example, the impact of pollutants from SACs on the global greenhouse effect can be uniformly measured by CO_2. Therefore, the characterization process can be expressed as

$$P_{co2} = CO_2 + \sum_{i=1}^{N_p} \lambda_i \times \Psi_i \tag{12}$$

where P_{co2} is the equivalent of CO_2 in the whole life cycle of SAC; N_p represents the number of pollution and emission sources; Ψ_i and λ_i denote the i-th pollution source and its corresponding equivalent coefficient, respectively.

The impacts of pollutions and emissions emitted in the whole life cycle of SACs can be divided into six parts: greenhouse effect, ozone layer destruction, eutrophication, acidification, human toxicity and natural pollution. During the whole life cycle of SAC, all greenhouse gas emissions are converted into carbon dioxide emissions, and all pollutants that destroy the ozone layer are converted into chlorofluorocarbon emissions. Similarly, eutrophication of water quality is converted to chemical oxygen demand. In addition, all emissions and pollutants that are acidified and toxic to humans and soil are converted to SO_2, CO and NH_4, respectively. Finally, the indirect environmental cost of the SAC over the entire life cycle can be computed by multiplying the equivalent emissions by their treatment costs per unit, as shown in the following equation:

$$C_{env}^{id} = \sum_{i=1}^{6} P_i \times \vartheta_i \tag{13}$$

where C_{env}^{id} represents the indirect environmental cost of SAC; P_i is a certain equivalent of emissions; ϑ_i denotes the treatment price. The calculation process of the indirect environmental cost of SAC is shown in Fig. 7.

Therefore, the eco-cost of SAC throughout the entire life cycle can be summarized as:

$$C_{gc} = C_{env}^{d} + C_{env}^{id} + C_{nenv}^{d} + C_{nenv}^{id} \tag{14}$$

where P_{gc} represents the eco-cost of SAC; C_{env}^{d} is the direct environmental cost; C_{nenv}^{id} and C_{nenv}^{d} stand for the direct

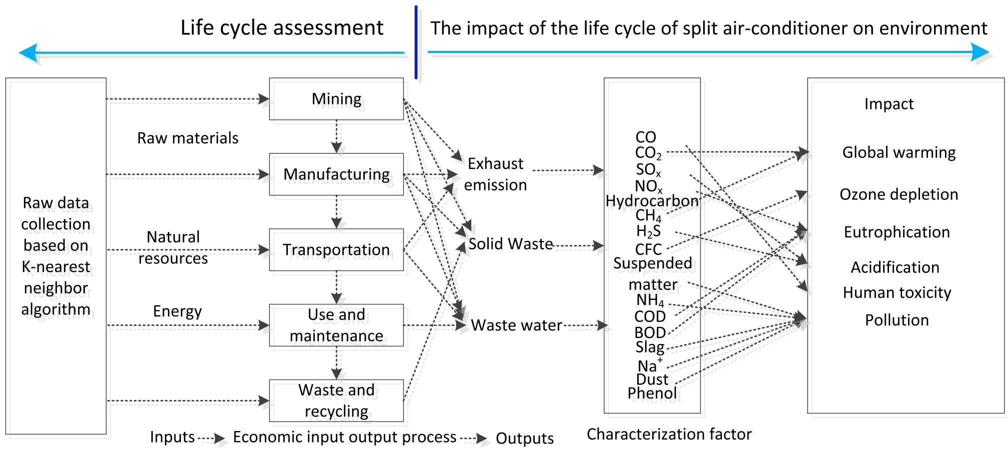

FIGURE 7. The evaluation process of indirect environmental cost of SAC.

non-environment cost and indirect non-environmental cost, respectively.

E. ADVANTAGES OF THE PROPOSED ECO-COST ANALYSIS

This study proposes an eco-cost assessment framework for SAC based on ABC method. Compared with the existing methods with similar topics, the proposed method has at least three advantages. First, the proposed method is more general than traditional methods and can also be applied for the eco-cost assessment of other home appliances such as refrigerator. Second, the proposed method exhibits high robustness because it can cope with the missing data in data collection process. Third, the proposed method has good compatibility. This is because various life cycle assessment methods based on PLCA or EIOLCA can be well integrated into the proposed eco-cost assessment method. In other words, the proposed method combines the life cycle assessment and life cost assessment, so it has a better compatibility than traditional eco-cost methods. In summary, the proposed eco-cost evaluation method of SAC has generality, robustness and compatibility, so it has a high potential in practical application.

IV. CASE STUDY

In this paper, the eco-costs of variable-frequency SAC and fixed-frequency SAC are evaluated to verify the feasibility and effectiveness of the proposed method.

A. EXPERIMENTAL SETTING

SAC is responsible for controlling the room temperature of the buildings and consists of an indoor unit and an outdoor unit. The indoor unit contains electrical control circuit components and indoor heat exchangers. The outdoor unit mainly includes a compressor and an axial flow fan. In general, SAC includes FFSAC and VFSAC. FFSAC refers to the SAC that basically keeps the compressor speed unchanged and relies on the compressor to be constantly on/off to adjust the indoor temperature. VFSAC refers to the SAC with an inverter. The compressor in VFSAC always operates in an optimal rotation speed, thereby achieving the purpose of energy saving. This is because the control system of the inverter can real-time tune the rotation speed of the compressor. It can be seen that the operating mechanisms of FFSAC and VFSAC are different. Therefore, the eco-cost analyses of these two types of SACs are carried out separately.

For eco-cost analysis, it is required to recycle a large amount of SACs to better measure their power consumptions in their whole life cycle. Therefore, we collect the component data of 621 VFSACs and 450 FFSACs from Chigo Air Conditioning Company in Guangdong, China. However, we found that there are some data or component missing in the recycled SACs. Or some data in the data collection process is obviously incorrect. We therefore use the KNN to deal with these problematic data. The basic information of these two types of SACs are shown in Table 2. The eco-cost boundary of the SACs is defined as the scope of the life cycle cost assessment of SAC, that is, the cost in the whole life cycle, the input cost and the output cost. International standards ISO 14040, ISO 14042 and PAS 2050 are used in this paper to baseline the cost assessment. All the materials and life cycle phases of SAC, including R&D, manufacturing, use and recycling, are statistically modeled on the Gabi software. The raw materials are listed in Table 1. The pollutants, emissions and power consumptions of SACs are mainly generated in the manufacturing phase and usage phase. In addition, we need to quantitatively analyze the correlation between environment, energy consumption and cost for the eco-cost analysis of SACs.

Based on the Gabi ecological database and the energy efficiency standards of SAC, we create the eco-mathematic energy consumption optimization formula and calculate the eco-cost estimate of SAC. First, we need to establish the eco-cost models of each life stage of SAC on Gabi software. The eco-cost model needs to consider the energy consumption during the manufacturing process of SACs, including component processing, assembly processing and auxiliary equipment design. According to our survey, the power consumption

TABLE 2. The basic information of two types of SAC.

	Weight	Size	Cooling capacity	Energy efficiency rating	Price	Refrigerant	Years of use
VF SAC	85.55kg	890mm×289mm×210mm	3.5kW	1	3895RMB	R410a/1120g	10
FF SAC	50.80kg	890mm×289mm×210mm	3.5kW	3	2899RMB	R410a/1120g	10

of the SAC equipment is about 0.12 kWh/kg. In the R&D stage, the design and manufacturing processes of all components of the indoor and outdoor units should be carefully considered. In the transportation phase, factors such as packaging, shipping and energy consumption should be considered, and in the usage phase, the maintenance cost and power consumption cost should be taken into account. At present, the domestic manufacturing technology of the SAC system is very mature, and the reliability of each component is high, so the air conditioner is an atypical maintenance product. In addition, it is possible to add a certain amount of refrigerant during use. However, due to the low maintenance probability and the infrequent occurrence of refrigerant replacement, this paper does not consider the replacement cost of refrigerant. In the recycling stage, we set the recovery of various original materials as follows: steel recovery rate is 75%, aluminum recovery rate is from 80% to 85%, copper recovery rate is from 80% to 85% and waste plastic recovery rate is about 25%. These recycling rates are collected from [37]. In addition, the disassembly during the recycling phase is carried out manually. The full life cycle cost model of the SAC built on Gabi software is shown in Fig. 8.

With the help of the established LCA model in Gabi, the direct environmental cost, indirect environmental cost, direct non-environmental cost and indirect non-environmental cost of the SAC can be estimated using the proposed eco-cost method based on ABC. The flowchart of the proposed eco-cost analysis is graphically shown in Fig. 8.

B. NUMERICAL RESULTS

In this study, the eco-cost assessment of SACs is realized using the real measured data of SACs. We first conduct the eco-cost analysis on VFSAC. Before that, a series of raw data of pollutants and energy consumptions of VFSAC are collected from Chigo Air Conditioning Company in Guangdong, China. The pollutants consisting of various wastes and emissions of VFSAC during its whole life cycle are shown in Fig. 9. These pollutants are measured by mass in kilometers. A point in Fig. 9 represents the mass of a certain pollutant in VFSAC's entire life cycle. For example, the value of the slag term is 319.89, which means that for each air conditioner, 319.89 kg of slag is required to be emitted to the natural environment. The energy consumption of the VFSAC in the manufacturing phase, transportation phase, use phase and recovery phase are 7774.34 MJ, 723.65 MJ, 56102.34 MJ and 916.22 MJ, respectively. It can be seen that the power consumption of the VFSAC mainly comes from the manufacturing stage and the usage stage, and the sum of the two types of energy accounts for 97.5% of the total power consumption. According to these pollutants, emissions and energy consumption data, we can evaluate the eco-cost of VFSAC over the entire life cycle based on the algorithm flow in Fig. 4. The obtained eco-cost results of VFSAC are given in Table 3.

TABLE 3. Eco-cost result of VFSAC.

Total eco-cost (RMB)	Manufacturing (RMB)	Transportation (RMB)	Recycling (RMB)	Usage (RMB)
18337.1	2169.3	202.6	256.5	15708.7

TABLE 4. Eco-cost of FFSAC.

Total eco-cost (RMB)	Manufacturing (RMB)	Transportation (RMB)	Recycling (RMB)	Usage (RMB)
29229.0	2518.6	202.6	256.3	26251.6

Then, we analyze the eco-cost of FFSAC. The pollutants and exhaust emissions of FFSAC throughout the whole life cycle are shown in Fig. 10. The energy consumption of FFSAC in the manufacturing phase, transportation phase, use phase and recovery phase are 8994.973 MJ, 723.65 MJ, 93755.52 MJ and 915.22 MJ, respectively. Similarly, the energy consumption of FFSAC is mainly concentrated on the manufacturing phase and the usage phase. Figs.9-10 demonstrate that many pollutants consisting of wastes and emissions are emitted to the nature environment, when a SAC is produced. In addition, large power consumptions of SACs also indirectly cause some damages on nature ecology because the power is generated by using fossil fuels. This indicates that SACs have some negative impacts on environment. The pollutants and energy consumption data of FFSAC are also collected from Chigo Air Conditioning Company. Thereafter, we adopt the proposed analysis method based on ABC to evaluate the eco-cost of FFSAC. The obtained results of FFSAC throughout the life cycle are shown in Table 4.

As can be seen from Table 3, the total eco-cost of VFSAC is 18337.1 RMB, and its eco-costs in the manufacturing, transportation, usage and recycling stages are 2169.3RMB, 202.6 RMB, 15708.7 RMB and 256.5 RMB, respectively. Obviously, the eco-cost of VFSAC in the usage stage is relatively high, which is mainly due to the high energy consumption in this stage. Similarly, Table 4 also shows that the

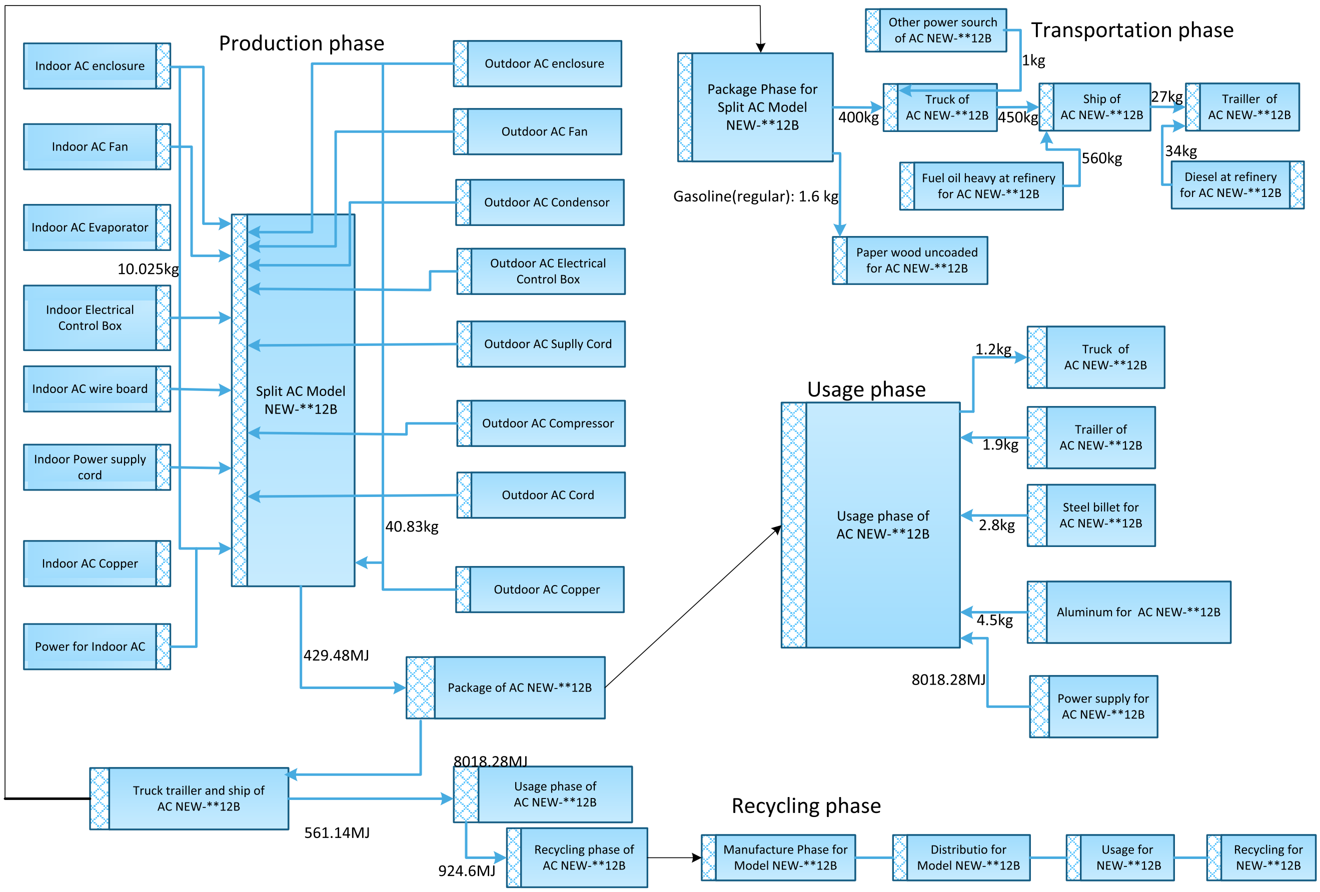

FIGURE 8. The eco-cost analysis model over the whole life cycle of SAC.

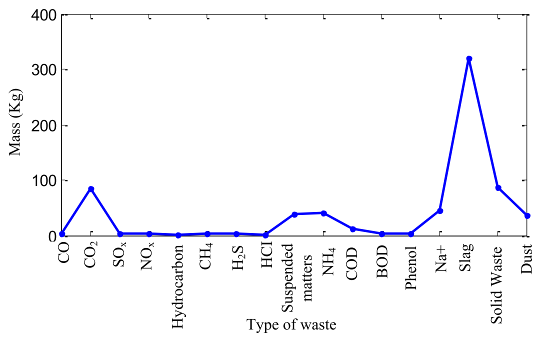

FIGURE 9. Wastes and emissions in the whole life cycle of VFSAC.

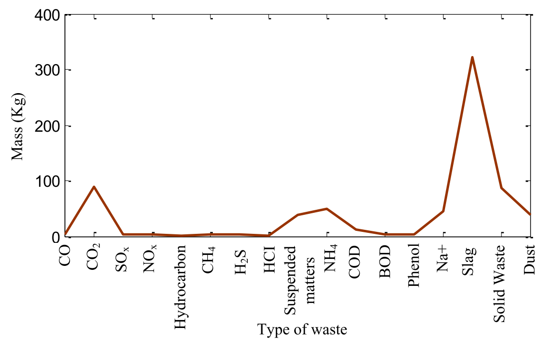

FIGURE 10. Wastes and emissions in the whole life cycle of FFSAC.

eco-cost of FFSAC in the usage stage is highest, which is 26251.6RMB, accounting for 89.81% of the total eco-cost. In addition, the eco-cost of VFSAC is much less than the eco-cost of FFSAC. This is mainly because FFSAC has a relatively low operating efficiency and thus consumes more energy during the usage phase. Tables 3-4 demonstrate that the proposed method based on ABC can be applied to evaluate the eco-cost of two types of SACs. The obtained results are consistent with the preliminary estimates of the eco-costs of these two types of SACs from Chigo Air Conditioning Company.

C. DISCUSSION

The ABC-based eco-cost assessment method proposed in this study has many application scenarios. It can not only be used to compare the eco-costs of different types of SACs, as shown in Tables 3-4, but also can be applied to analyze the main factors affecting the eco-cost of SACs. In this subsection, we adopt the proposed method to analyze the relationship between energy efficiency deviation of SAC and its corresponding eco-cost, thereby demonstrating that the proposed method has a high potential in practical applications.

TABLE 5. Annual power consumption of SACs under different conditions.

Type	Cooling	Thermostat	Standby	Sum
VFSAC	1285kW	7.072kW	21.42kW	1313.49kW
FFSAC	2125kW	10.608kW	23.562kW	2159.17kW

TABLE 6. Nominal Eco-cost of two types of SACs.

Type	Total eco-cost (RMB)	Manufacturing (RMB)	Transportation(RMB)	Recycling (RMB)	Usage (RMB)
VFSAC	15763.4	2169.3	202.6	256.5	13135.0
FFSAC	24569.2	2518.6	202.6	256.3	21591.7

The eco-cost analysis in Section IV-B is the real eco-cost obtained using the energy consumption data measured by Chigo Air Conditioning Company. However, we also can calculate an eco-cost result when we use calibrate energy efficiency grade of SACs in the manufacturing process. According to the energy efficiency grade and the Chigo company's annual energy consumption, the life cycle power consumption of the SAC can be estimated, so that the calibration eco-cost of the SAC can be obtained. The annual power consumptions of VFSAC and FFSAC under cooling, thermostat and standby operating conditions are shown in Table 5.

Undoubtedly, there will be a certain difference between the calibrated energy consumption and the actual energy consumption of the SAC. The negative deviation of the energy consumption of the FFSAC is -12%, and that of VFSAC is about -10%. Here, we also assume that the statistical energy consumption data of SACs is normally distributed. According to the proposed method based on ABC, we can calculate the nominal eco-cost of the SAC. The obtained results are shown in Table 6.

Regarding Tables 3-4 and Table 6, we can see that the -12% energy consumption deviation of FFSAC directly led to an increase of 15.94% in its eco-cost. Similarly, -10% the energy consumption deviation of VFSAC during the use phase results in an increase in eco-cost of 14.03%. Therefore, it is important to assess the actual energy consumptions of SACs during their use phases to assess their eco-costs. In addition, we can also see that the eco-costs of FFSAC and VFSAC are the same during the transportation and recycling phases. In the manufacturing phase and the use phase, the eco-cost of the VFSAC is substantially lower than the eco-cost of the FFSAC. It can be seen that the VFSAC has great advantages in environmental protection. In addition, Table 6 shows that the eco-costs of the VFSAC in the manufacturing, transportation, usage and recycling phases account for 13.76%, 1.28%, 83.32% and 1.63% of the total eco-cost, respectively. It can be seen that the usage phase has the greatest impact on eco-costs, while the transport phase has the least impact on the final eco-cost.

The above results and analysis demonstrate that the proposed method can be applied to the eco-cost assessment of SAC. The calculated eco-cost is the estimate of the economic cost for addressing the negative impact of SAC on the environment. Therefore, the proposed eco-cost analysis method helps the relevant national departments and industrial technical personnel to understand the eco-costs of SACs, thereby further reducing environmental pollution and energy crisis.

V. CONCLUSION

Eco-cost analysis plays a critical role in reducing pollutions and finding promising solutions for global energy crisis. Therefore, this study proposes a new eco-cost assessment method for SACs. In this method, a KNN-based method is developed to deal with the problematic data missing in the data collection process. Then, environmental cost and non-environmental cost assessment structures of SACs based on an ABC method are developed accordingly. The final eco-cost of SACs can be obtained by aggregating the environmental and non-environmental costs. To the best of our knowledge, this study is the first attempt to evaluate the eco-cost assessment of SACs. Finally, this study collects a large quantity of SACs, and their component data can be obtained. Consequently, the eco-cost assessments of VFSAC and FFSAC are performed on the Gabi software. The obtained results show that the proposed method is feasible to estimate the eco-cost of SACs, and has a wide range of applications, such as quantitatively analysis of the relationship between energy efficiency deviation of SAC and its corresponding eco-cost.

The main limitation of the proposed eco-cost analysis method is that its estimation accuracy hugely relies on a large amount of component data. Overcoming this limitation is our future research work. In addition, our potential future works also contain how to properly evaluate the proposed eco-cost analysis method, and how to apply this method on the eco-cost analysis of other home appliance such as refrigerator. Therefore, this study is helpful for the policy-makers to assess the economic costs for protecting the nature environment.

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