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Economic and Environmental Assessment of Carbon Emissions from Demolition Waste Based on LCA and LCC

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Abstract: In China, urban renewal and renovation projects generate a large amount of demolition waste every year, the disposal of which has certain impacts on the environment. Therefore, more effective policies should be implemented for the management of demolition waste. This study combines life cycle assessment (LCA) with life cycle costing (LCC) to analyze the environmental and economic drivers of three different waste disposal scenarios in Guangzhou, China, in the context of carbon trading: S1 (landfilling), S2 (recycled aggregate), and S3 (recycled powder). In this study, the carbon emissions of demolition waste were obtained by LCA, and the carbon emission cost was calculated based on the carbon price in the carbon trading market of Guangdong Province. The LCA results showed that waste recycling can greatly reduce carbon emissions. The results showed that compared to S1, S2 reduced 6.790×10^8 kg CO_2 eq. Additionally, S3 reduced 4.172×10^8 kg CO_2 eq. compared to S2. The LCC results show that waste recycling can greatly reduce the total costs of the demolition sector, while the production of recycled powder can generate 57.35% of the revenue from recycled aggregate to the recycling plant. This study combines LCA and LCC, and considers environmental factors to assess the economic results using carbon emissions cost, thereby forging a new exploration method in the field of life cycle theory. The findings of this study could provide a basis for the formulation of a new demolition waste management policy. In the case of the gradual implementation of carbon trading, it could also provide new ideas for current demolition waste treatment from economic and environmental perspectives.

Keywords: demolition waste; recycling; carbon emissions; environmental assessment; LCA

1. Introduction

Global warming is intensifying, and climate change is closely related to human production and life. China produces an enormous amount of carbon emissions and is under great pressure to reduce them. The construction industry not only promotes the development of the national economy, but also contributes to a large volume of carbon emissions. According to statistics, approximately 40% of the world's annual consumption of resources is related to the construction industry, which produces 36% of the world's total CO_2 and 35% of the world's total waste annually [1]. It is difficult for industries to significantly reduce their emissions; however, the construction industry has great potential for reducing emissions, and it should be easy to achieve the desired reduction [2].

Construction and demolition waste (CDW) refer to the waste generated during the construction and demolition of buildings, usually including concrete, brick, tile, wood, and glass. The nature of demolition waste can vary widely from one place to another [3]. Recently, China has been generating two to three billion tons of CDW every year, about 70% of which is demolition waste [4,5]. Because the amount of demolition waste is greater than that of construction waste, this study focuses on demolition waste. At present, demolition waste disposal methods mainly include reuse, recycling, landfill, and dumping [6]. The main purpose of recycling is to make recycled aggregate to replace natural aggregate. However, a large proportion of demolition waste is buried rather than recycled. Current policies on demolition waste disposal have many drawbacks, and industry standards for the different disposal approaches are not efficient. In recycling, a large amount of demolition waste is used as roadbed or filling materials for road construction [7]. In addition to road construction, the most extensive recycling method is the use of recycled aggregate for concrete production, which is a more advanced approach than road construction [8]. In the Lisbon area, this method of waste recycling has reduced the use of natural aggregate, thus increasing the economic value of recycled aggregate [9]. However, in China, the cost of producing recycled aggregate is likely to be higher than that of the natural aggregate because of the high costs of energy consumption, machines, etc. Therefore, more detailed studies are required to evaluate the economic feasibility of producing recycled aggregate.

Life cycle assessment (LCA) refers to the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [10]. It is a comprehensive assessment that considers all aspects of the natural environment, human health, and resources. Its unique feature is the focus on the entire life cycle of the product, to avoid problem shifting [11]. Life cycle costing (LCC) is a process that determines the sum of all the costs associated with an asset or part thereof, including the acquisition, installation, operation, maintenance, refurbishment, and disposal costs [12].

In the past, much of the research on CDW analyzed the environmental and economic impacts separately, while only a few analyzed both simultaneously. Previous studies focused on construction and demolition wastes simultaneously; however, a few studies focused on demolition waste alone. Borghi et al. [13] used LCA to conduct an environmental impact assessment of Italy's current CDW management and found that environmental impacts outweighed the benefits when CDW was used for road construction. Yazdanbakhsh et al. [14] focused on the application of CDW recycled aggregate. After comparing the environmental impacts of using recycled aggregate with that of natural aggregate in the production of concrete, they found that using a large amount of recycled aggregate concrete did not significantly reduce the adverse environmental impacts. Hossain et al. [15] found that the environmental impacts of producing ordinary Portland cement were mainly related to the import of raw materials and the burning of fossil fuels. Therefore, using recycled powder instead of cement would yield better environmental outcomes. All these studies focused on the environmental assessment of CDW using the LCA method.

The economic assessment of CDW is more diverse. Begum et al. [16] analyzed the costs and benefits of CDW reduction and found that the economic benefits of recycling construction waste could be as much as 2.5% of the total project budget. Yuan et al. [17] used system dynamics to analyze the costs and benefits of CDW management from a dynamic perspective and found that CDW management can yield net benefits; high landfill fees also bring high benefits. Coelho and de Brito [18] analyzed the economic viability of a large CDW recycling plant in Lisbon and found that the revenue from the sale of recycled aggregate and gate fees could exceed the initial investment in a few years.

A few studies have looked at both the environmental and economic properties of construction waste. Braga et al. [19] compared the environmental impact and economic benefits of recycled aggregate concrete to those of natural aggregate concrete. The results showed that recycled aggregate concrete is not only more environment-friendly, but also cheaper to manufacture. Compared to LCA, LCC has less application in CDW [20]. In fact, a combination of LCA and LCC can be used to analyze the environmental and economic impacts of construction waste. LCA and LCC share the same system boundary, which can effectively enhance the correlation between the environmental impact and economic benefits in the analysis [21]. In addition, the existing research primarily compares the difference between landfill and recycling; however, when it comes to specific recycling approaches, most of the research has focused on recycled aggregate, only a few on recycled powders.

It must also be considered that according to China's carbon trading mechanism, enterprises that have not used their quota for carbon emissions can sell the remainder to enterprises having an insufficient quota. Therefore, the trading price of carbon emission quota becomes one of the costs of business and needs to be considered in the economic assessment of CDW using LCC analysis. As mentioned above, the combination of LCA and LCC can effectively enhance the correlation between environmental impact and economic benefits. The results of LCA can provide a basis for the calculation of LCC. The carbon emission cost obtained by LCA can be combined with the carbon price in the actual carbon trading market to calculate the total cost of the corresponding emissions, which can be used as the carbon emission cost in LCC [22].

In this study, LCA and LCC were combined to conduct environmental and economic assessments of different demolition waste disposal approaches. In this study, the carbon trading mechanism is used as a bridge, carbon emission costs are included in the total cost, and environmental factors are considered as economic results to improve the combination of LCA and LCC. This study can provide a basis for the formulation of low-carbon policies and provide new ideas for demolition waste disposal from an economic perspective under the circumstances of gradually implementing carbon trading.

2. Methods

2.1. LCA/LCC Framework

LCA and LCC share the same system boundaries and assumptions. LCA assesses the environmental performance of products, while LCC provides decision-makers with a cost-benefit analysis of different solutions from an economic perspective [23]. Decision-makers need to consider both environmental and economic factors when formulating CDW management policies. LCA and LCC complement each other in the decision-making process, and are simplified owing to common system boundaries and assumptions. In this study, both LCA and LCC involve four steps [10]: (1) Goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

2.2. Goal and Scope Definitions

In this study, LCA was mainly used to study carbon emissions without considering environmental impacts. Thus, the goal of the LCA was to identify the driving factors for carbon emissions in different demolition waste management scenarios. The goal of the LCC was to identify the economic drivers of the different demolition waste management scenarios.

This study mainly evaluated the waste generated during the demolition of buildings; the life cycle of the demolition waste starts with the demolition and ends with its final disposal. Specifically, it can be divided into three stages: Generation, transportation, and disposal. During the generation stage, after a building is demolished, the waste is collected and sorted. During the transportation stage, the waste is transported to the corresponding disposal site, determined according to the waste type. During the disposal stage, different wastes are disposed of in different or the same way as per their type.

In this study, waste was classified into three categories: (A) Metal, timber, plastic, and glass; (B) cement, concrete, bricks, and tiles; and (C) mixed fragments. Metal, timber, and plastic are all for sale. However, in practice, the demolition waste from most old urban areas primarily consists of brick and concrete, with few other materials. Some owners feel that the sorting cost is too high and send the unsorted waste to landfills for convenience. To make this study more complete and comprehensive, and to compare it with other scenarios, this study also analyzed the landfilling of group A wastes. Group B wastes were the focus of this study, and landfilling and recycling processes were analyzed. Recycled wastes can be classified into two types depending on the processing methods: Recycled aggregate and recycled powder. However, not all wastes in group B can be processed into recycled powder; therefore, most of them were processed into recycled aggregate. Wastes in group C cannot be recycled and can only be landfilled. According to different disposal methods, this study analyzed three different scenarios: (S1) Landfilling, (S2) recycled aggregate production, and (S3) recycled powder production (see Figure 1).

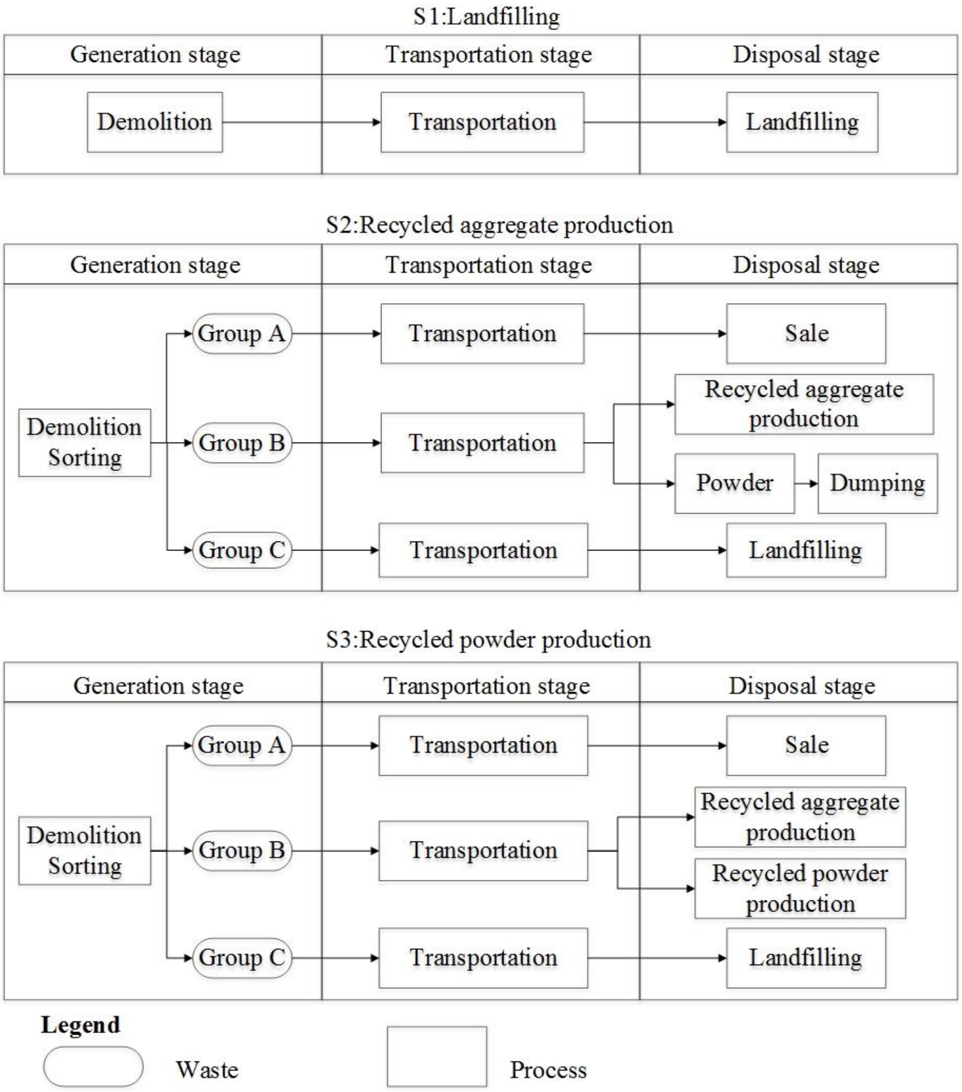

Figure 1. System boundaries of the three scenarios: (S1) Landfilling, (S2) recycled aggregate production, and (S3) recycled powder production.

For the different scenarios to be comparable, the functional units in the LCA and LCC studies must be consistent. Therefore, the disposal of waste generated by a demolition project was set as the functional unit of this study. The system boundaries of each scenario are shown in Figure 1. In S1, the building was mechanically and manually demolished, and the waste was transported to the landfill for disposal. In S2, after the demolition of the building, simple crushing was mechanically and manually carried out on-site, and the produced group A wastes were transported to the market for sale. The group B wastes were transported to the recycling plant for treatment, and then processed into recycled coarse aggregate by crushing, screening, etc. Recycled coarse aggregate can replace the stones in concrete; hence, the recycled coarse aggregate was sold to the ready-mix concrete yard. Group C wastes were transported to a landfill for disposal. In S3, group A and C wastes were treated in the same way as in S2. The only difference was that group B wastes with larger particle sizes were processed into recycled coarse aggregate by crushing and screening, while those with smaller particle sizes were mixed, homogenized, pulverized (by a centrifugal ball mill), and processed into recycled powder. This recycled powder accounted for 10–20% of the total group B wastes [24]. To simplify the calculation, it was assumed that the mass of recycled powder accounted for 15% of the total mass of the raw materials. The powder was also generated in S2, but was dumped directly into the recycling plant and not processed into recycled powder. Recycled aggregate accounted for 85% of the raw material quality.

Scrap metal needs to be treated after being sold before it can be used. In fact, there is a loss rate for all waste types in the transportation or recycling process, and group A waste may not completely replace the raw materials. However, to simplify our calculations, this study assumed that the group A wastes could completely replace the same amount of raw materials and that the recycled aggregate could completely replace natural aggregate without affecting the performance of concrete after the treatment of group B wastes. As for the recycled powder, previous research shows that when it is used to replace less than 30% of cement, its effect on concrete performance is not significant [25]. At present, the output of recycled powder in the market is low (less than 30% of the output of cement). Therefore, this study assumed that the total amount of recycled powder produced is completely absorbed by the market; in other words, the production of cement (of the same quality) for concrete production is reduced.

2.3. Inventory Analysis

In the inventory analysis stage, all data within the system boundaries need to be collected. LCA data included all energy and material inputs and outputs within the scope of this study, while LCC data included financial cash flows. In the collection of data, there are often great differences due to time, region, technology, etc. Therefore, we tried to collect data from within the study area. The life cycle of demolition waste is short; thus, the time value of money was not considered in the LCC. The data in this study were obtained from research in Xiancun, Guangzhou. If data were difficult to obtain, they were obtained from the literature, which mainly focused on research in China.

In this study, according to the different life stages of waste, we classified the associated activities into four sectors: Demolition, transportation, landfill, and recycling plant. The demolition sector is responsible for the on-site demolition and sorting of waste for the entire demolition project, and the transportation sector is responsible for transporting the waste generated from the demolition to various locations. Each sector has different activities. The carbon emissions and economic cost of the different activities were calculated by adding the values from each sector to determine the total life cycle carbon emissions and costs of the demolition waste. In this step, the Life Cycle Inventory (LCI) calculation model for demolition waste was also established (see Figure 2).

The demolition sector is sector 1, transportation sector is sector 2, recycling plant is sector 3, and landfill plant is sector 4; C_n is the total cost of sector n (n = 1,2,3,4).

Equations (1)–(10) are the corresponding calculation formulas, and the notations in the formulas are explained in Table A1 (Appendix A).

$$C_n = C_{Dn} + C_{En} \tag{1}$$

$$C_{Dn} = \sum C_{Am} \tag{2}$$

$$C_{Am} = C_M + C_L + C_O - I \tag{3}$$

$$C_M = \sum R_x{\cdot}V_x{\cdot}D_x \tag{4}$$

$$C_L = T{\cdot}S \tag{5}$$

$$C_{En} = E_n{\cdot}P \tag{6}$$

$$E_n = \sum E_{Am} \tag{7}$$

$$E_{Am} = E_M + E_O - E_R \tag{8}$$

$$E_M = \sum V_x \cdot D_x \cdot e_x \cdot f_e \quad (9)$$

$$P = P_A \quad (10)$$

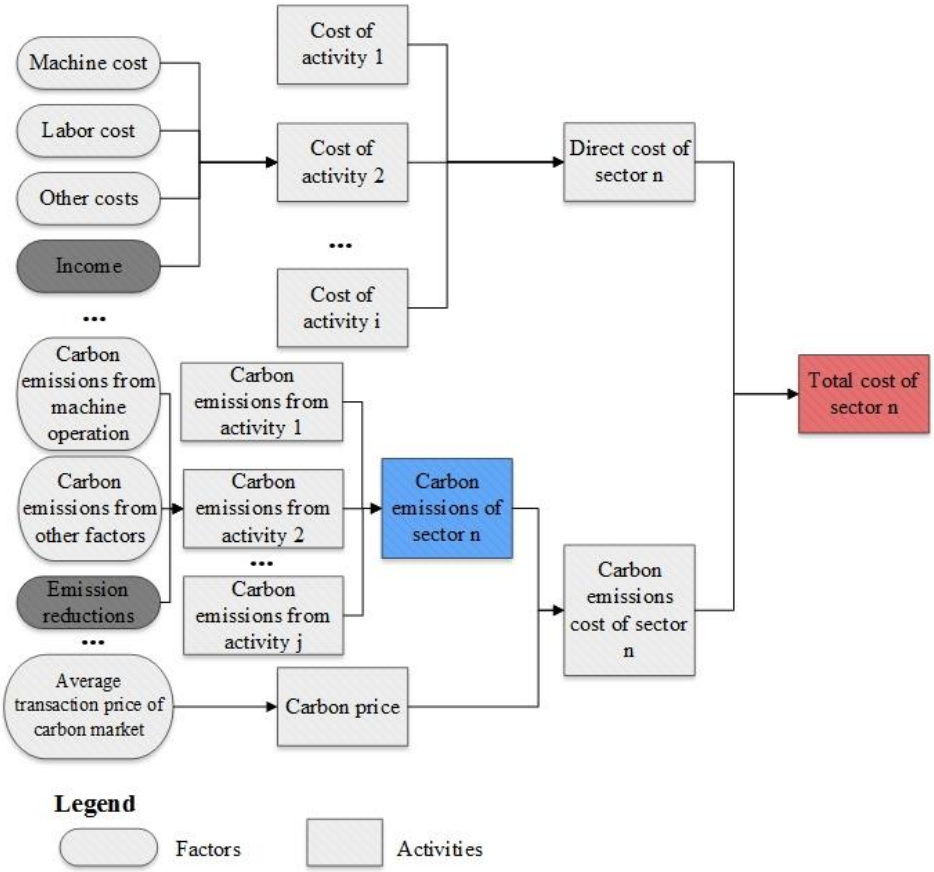

Figure 2. Demolition waste LCI calculation model.

2.3.1. Cost of Demolition Sector

When n = 1, C_1. is the total cost of sector 1. The demolition sector includes four activities, and the corresponding activity costs are as follows: Cost of demolition and sorting, cost of selling group A waste, cost of disposing of group B waste, and cost of landfilling waste.

The cost of dismantling and sorting consists of mechanical and labor costs, while other costs and income are 0, is as follows. In Equation (11), C_{A1} is the cost of dismantling and sorting (unit: USD), C_M is the mechanical cost (unit: USD), and C_L is the labor cost (unit: USD).

$$C_{A1} = C_M + C_L \quad (11)$$

In the cost of selling group A waste, mechanical and labor costs are 0, while other costs are mainly related to transportation.

In Equations (12) to (16), C_{A2} is the cost of selling the wastes from group A (unit: USD), C_O is other costs (unit: USD), I is income (unit: USD), C_{TRA} is the cost of transporting group A waste to the market (unit: USD), I_{SA} is the sales revenue of group A wastes (unit: USD), W_r is the weight of material r in group A wastes (unit: t), P_r is the selling unit price of material r (unit: USD/t), W_A is the total weight of group A wastes (unit: t), P_T is the transportation unit price (unit: USD/t × km), and D_A is the transportation distance (unit: km) from the demolition site to the market. The cost of disposing of group B waste and the landfill cost of group A waste were calculated in a way similar to the cost of selling group A wastes.

The cost of selling group A waste is the only source of income; therefore, the calculation equations are as follows (Equations (12)–(16)):

$$C_{A2} = C_O - I \tag{12}$$

$$C_O = C_{TRA} \tag{13}$$

$$I = I_{SA} \tag{14}$$

$$I_{SA} = \sum W_r \cdot P_r \tag{15}$$

$$C_{TRA} = W_A \cdot P_T \cdot D_A \tag{16}$$

The carbon emissions from the demolition sector consist of carbon emissions from the demolition and sorting activities, and that from the sale of group A wastes.

Carbon emissions from demolition and sorting activities only contain mechanical carbon emissions.

In Equation (17), E_{A1} is the carbon emissions from demolition and sorting activities (unit: t), while E_M is the carbon emissions from machine operation (unit: t).

The equation is as follows:

$$E_{A1} = E_M \tag{17}$$

When selling group A wastes, there are only emission reductions, with no other carbon emissions.

In Equations (18)–(20), E_{A2} is the carbon emissions (unit: t) from selling group A wastes, E_R is the quantity of emission reduction (unit: t), E_{RRM} is the quantity of carbon emissions reduced by replacing raw materials (unit: t), W_r is the amount of substitute raw material r (unit: t), and f_r is the carbon emissions factor (unit: kg CO_2 eq./t) of raw material r.

The equations are as follows:

$$E_{A2} = -E_R \tag{18}$$

$$E_R = E_{RRM} \tag{19}$$

$$E_{RRM} = \sum W_r \cdot f_r \tag{20}$$

2.3.2. Cost of Transportation Sector

When n = 2, C_2 is the total cost of sector 2. The transportation sector includes three activity costs: Cost of transporting group A waste to the market, cost of transporting group B waste to the recycling plant, and the cost of transporting waste to the landfill plant. Carbon emissions from the transport sector come from three activities: Transportation of group A waste from the demolition site to the market, transportation of group B waste to a recycling plant, and transportation of waste to the landfill plant.

2.3.3. Cost of Recycling Plant

When n = 3, C_3 is the total cost of sector 3. The recycling plant sector includes only the cost of waste treatment. The carbon emissions from the recycling plant include those from waste treatment, which include those from machine operation minus any emission reductions.

2.3.4. Cost of Landfill Plant

When n = 4, C_4 is the total cost of sector 4. The landfill plant sector includes only the cost of landfilling. Carbon emissions from the landfill plant include those from the landfill, which includes carbon emissions from machine operation and other carbon emissions.

2.4. Impact Assessment

2.4.1. Life Cycle Impact Assessment

Carbon emissions are used as the assessment criteria for different scenarios in the life cycle impact assessment (LCIA). Since CO_2 is not the only gas that contributes to global warming [26], global warming potential should be used to describe the extent to which emissions contribute to climate change. The carbon emission factors cited in this study reflect the global warming potential, not just CO_2 emissions. CO_2 eq. is used in this study to represent carbon emissions. Carbon emissions from the demolition sector include those from machine operation and reductions resulting from replacing raw materials with recycled materials, while those from the transportation sector include only vehicular emissions. Carbon emissions from the recycling plant include those from machine operation and reductions, and those from the landfill plant include emissions from machine operation and chemical reactions that occur in the landfill. Finally, the carbon emissions from each sector in each scenario were added to obtain the total carbon emission for the entire life cycle of the demolition waste, as follows.

In Equation (21), E_{ALC} is the carbon emissions (unit: kg) during the entire life cycle of demolition waste.

$$E_{ALC} = \sum E_n \tag{21}$$

2.4.2. Economic Assessment

In the inventory analysis stage, the LCI calculation model for demolition waste was established, and in the LCC stage, the total cost of sector n was used to assess the economic benefits of each sector in each scenario. For the demolition sector, the cost includes machine, labor, transportation, landfill, disposal, and carbon emissions costs, and income from the sale of group A waste. For the transportation sector, the cost includes vehicle cost, carbon emissions cost, and transportation revenue. The cost of the recycling plant includes machine, labor, and carbon emissions costs, and income from the disposal fees and sale of recycled materials. The cost of the landfill plant includes machine costs, labor costs, and income from landfill fees.

2.4.3. Environmental and Economic Sensitivity Analyses

The accuracy of LCA and LCC results depends largely on the reliability of inventory data; uncertain and unrepresentative data can have serious consequences during the inventory analysis stage [27]. Sensitivity analysis is needed to identify the uncertainty of the input data. Sensitivity analysis can be used to evaluate the degree of change in the final result owing to changes in the input data.

This research conducted sensitivity analyses on both environmental and economic results. When only a single parameter was changed, the sensitivity rate (S_R) was determined according to the ratio of the magnitude of change in the result to that of the parameter, as follows.

In Equation (22), S_{Ri} is the sensitivity rate of parameter i, Δr is the change amplitude of the result, I_r is the initial result, ΔP_i is the change amplitude of parameter i, and I_{pi} is the initial value of parameter i.

$$S_{Ri} = \frac{\frac{\Delta r}{I_r}}{\frac{\Delta P_i}{I_{pi}}} \tag{22}$$

Both environmental and economic assessments were conducted in this study; however, economic assessments need to be sector-based, whereas environmental assessments can be performed for the whole process of the production of demolition waste. Therefore, in the environmental sensitivity analysis, this study considered the carbon emissions from the whole life cycle of demolition waste as the result, while the economic sensitivity analysis considered the total cost of each sector as the result.

3. Case Study

3.1. *Case Description*

For the case study, a reconstruction project in an old urban area of Guangzhou, Guangdong province, China (Figure 3) was selected. The project is located in Xiancun, southwest of Tianhe district, Guangzhou (23°12′ N and 113°32′ E). The total land area of Xiancun is 18.49 ha. Most buildings were multi-story buildings. The area had high building density and small building spaces. The total building area was 720,000 m^2, and a total of 1,258,324.36 t of waste was generated from demolition. The specific components of the demolition waste were determined by a local on-site survey in Xiancun (see Table A2, Appendix B).

Figure 3. Xiancun old urban area reconstruction project.

3.2. *Inventory Analysis*

The demolition project was contracted by a local demolition company in Guangzhou. During the demolition process, human labor and machines such as excavators and rock drills were used, and the waste generated included metal, plastic, timber, glass, mortar, brick, tile, concrete, and mixed fragments. Group A waste (metal, plastic, wood, and glass) was sold to the market, group B waste (brick, mortar, tile, and concrete) was transported to the recycling plant for recycling, and group C waste (mixed fragments) was landfilled, as in S2. Through on-site surveys of demolition projects and interviews with related companies, inventory data for machines and labor were obtained, including the working efficiency of the machines, energy type, energy consumption rate, cost per unit time, labor efficiency, labor wages, disposal fees, and transportation costs (see Table A3 (Appendix C) and Table A4 (Appendix D)). Through interviews with the transportation department, the inventory data for the transportation process, including vehicle energy consumption and load (see Appendix D and Table A5 (Appendix E)), were obtained. Through surveys of local markets in Guangzhou, the selling prices of group A wastes, such as used steel, recycled aggregate, and recycled powder, were obtained (see Appendix D). Because of the need to analyze different scenarios, we obtained the information for S2 and S3 from estimates provided by relevant companies. In addition, because the transportation destinations and distances to those sites varied according to the different types of waste, it was assumed that the distance from the demolition site to each destination was 50 km. Data on carbon emission factors cannot be obtained from on-site surveys; hence, these data were obtained through relevant literature and databases (Tables 1 and 2). Luo [28] suggested setting the carbon factor for electricity at 0.68653 kg CO_2 eq./kWh. The carbon emission factors for diesel fuel, the raw materials replaced by group A waste, and the chemical reactions of group B and C landfilled wastes were obtained from IPCC 2013 GWP 100a V1.01. The carbon emission factors for natural coarse aggregates and cement were obtained from Li and Liu [29], and the carbon emission factors for the chemical reactions of group A landfilled waste were obtained from Wang [30].

Table 1. Carbon emission factors for unit energy.

Energy Type	Carbon Emissions Factor	Unit	Source
Diesel	4.16015	$kgCO_2$ eq./kg	IPCC 2013 GWP 100a V1.01.
Electricity	0.68653	$kgCO_2$ eq./kwh	Luo [28]

Table 2. Carbon emission factors of raw material reductions and chemical reactions.

Waste Materials	Raw Materials Replaced	Carbon Emissions Factors of Raw Material Reduction ($kgCO_2$ eq./t)	Carbon Emissions Factors of Chemical Reaction ($kgCO_2$ eq./t)
Steel	Steel	2268.6477 [a]	454.8083 [c]
Timber	Timber	919.2599 [a]	5102.6140 [c]
Plastic	Plastic	1866.6075 [a]	6189.0300 [c]
Aluminum	Aluminum	20,074.1686 [a]	454.8083 [c]
Glass	Glass	1166.5981 [a]	55.5330 [c]
Masonry material waste	Natural coarse aggregate	200,000 [b]	8.7033 [a]
Mixed fragments	Cement	24,900,000 [b]	14.1736 [a]

[a] Data from IPCC 2013 GWP 100a V1.01 [31]. [b] Data from Li and Liu [29]. [c] Data from Wang [30].

3.3. Interpretation

3.3.1. Environmental Results

This study used the carbon emission values determined by the environmental LCIA (see Figure 4) and calculated the proportion of emissions generated by activities within each scenario (see Table A5, Appendix F).

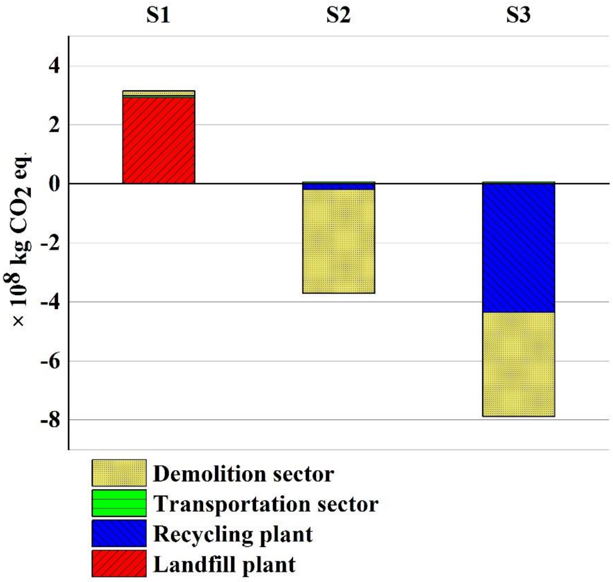

Figure 4. Environmental life cycle impact assessment (LCIA) results.

As shown in Figure 4, carbon emissions resulting from S1 were the highest of the three scenarios (3.147×10^8 kg CO_2 eq.), followed by those from S2 (-3.642×10^8 kg CO_2 eq.) and S3 (-7.814×10^8 kg CO_2 eq.). In S1, the landfilling of plastics produced the highest carbon emissions (56.64% of the total), amounting to 1.782×10^8 kg CO_2 eq. Mechanical operation during the demolition produced the highest carbon emissions in S2 (−4.47% of the total), amounting to 0.163×10^8 kg CO_2 eq. The S2 final carbon emissions were negative owing to the decreased need for raw materials that resulted from the recycling of group A wastes. Among them, the carbon emissions reduced by recycling aluminum were the highest at 1.678 × 10^8 kg CO_2 eq., accounting for 46.06% of the total carbon emissions in S2. Similarly, carbon emissions from S3 were also negative. The recycling of group A waste reduced a large quantity of carbon emissions, with the largest reduction resulting from the replacement of cement with recycled powder. This resulted in 4.216 × 10^8 kg CO_2 eq., 53.96% of the total carbon emissions in S3. Table 3 shows the percentage of carbon emissions from each activity with respect to the total carbon emissions.

Table 3. Contribution of each activity to life cycle assessment (LCA) results (%).

Activities	Details	S1	S2	S3
Demolition sector		5.16%	96.59%	45.02%
Carbon emissions from machine operation	Machine operation on demolition site	5.16%	–4.47%	–2.08%
Carbon emissions from replacement of raw materials	Recycling steel	/	35.88%	16.72%
	Recycling timber	/	3.63%	1.69%
	Recycling plastic	/	14.76%	6.88%
	Recycling aluminum	/	46.06%	21.47%
	Recycling glass	/	0.73%	0.34%
Transportation sector		1.95%	–1.68%	–0.78%
Carbon emissions from vehicle operation	Carbon emissions from vehicle operation during transportation	1.95%	–1.68%	–0.78%
Recycling plant		0.00%	5.16%	55.79%
Carbon emissions from machine operation	Machine operation in the recycling plant	/	–0.11%	–0.62%
Carbon emissions from replacement of raw materials	Recycled aggregate replacing raw materials	/	5.27%	2.46%
	Recycled powder replacing raw materials	/	/	53.96%
Landfill plant		92.89%	–0.07%	–0.03%
Carbon emissions from machine operation	Machine operation in the landfill plant	0.13%	0.00%	0.00%
Carbon emissions from chemical reactions in the landfill	Landfill of steel	8.32%	/	/
	Landfill of timber	23.35%	/	/
	Landfill of plastic	56.64%	/	/
	Landfill of aluminum	1.21%	/	/
	Landfill of glass	0.04%	/	/
	Landfill of group B waste	3.12%	/	/
	Landfill of group C waste	0.08%	–0.07%	–0.03%
Total		100.00%	100.00%	100.00%

The total carbon emissions resulting from S2 (−3.642 × 10^8 kg CO_2 eq.) were less than those from S1. This was mainly because, in group A, waste was no longer landfilled, but sold on the market, avoiding large amounts of carbon emissions generated by chemical reactions in the landfill. In S2, the carbon emissions from recycling group A waste were –3.681 × 10^8 kg CO_2 eq., and the production of recycled aggregate (1.919 × 10^7 kg CO_2 eq.) also reduced emissions. Recycling reduces carbon emissions; however, sorting of waste requires more machines. In addition, the treatment of group B wastes also required machines; therefore, the carbon emissions from machine operation in the demolition sector in S2 (1.628 × 10^7 kg CO_2 eq.) were higher than those in S1. The recycling plant also produced carbon emissions from machine operation (4.070 × 10^5 kg CO_2 eq.). However, the landfill plant only needed to landfill group C waste, so the carbon emissions from the landfill plant were greatly reduced (2.552 × 10^5 kg CO_2 eq.). The carbon emissions from the transportation sector were almost unchanged (6.125 × 10^6 kg CO_2 eq.).

The carbon emissions resulting from S3 were also negative. However, S3 included the processing of recycled powder; thus, the carbon emissions resulting from the machine operations of the recycling plant (4.847 × 10^6 kg CO_2 eq.) in S3 were higher than those in S2. However, the carbon emissions resulting from this extra machine operation were far less than the reductions that resulted from the replacement of raw materials with recycled powder (4.216 × 10^8 kg CO_2 eq.), while the carbon emissions from other sectors did not change. Thus, the total carbon emissions resulting from S3 (−7.814 × 10^8 kg CO2 eq.) were far less than those from S2. It can be seen from the above data that the carbon emissions reduced by the production of recycled powder in this case were 4.172 × 10^8 kg CO_2 eq., indicating that the production of recycled powder significantly reduced emissions.

3.3.2. Economic Results

This study used the total cost of each sector as the economic result (Figure 5) and analyzed the economic result for each sector under different scenarios. In S2 and S3, the total cost of the recycling plant was negative, indicating more revenue than expenditure. The results for S1 were larger than those for S2 and S3, with the cost of the demolition sector being positive, while the costs of the transportation sector and landfill plant were negative. This indicates that the expenditures in the demolition sector were higher than the income, while the incomes in the transportation sector and landfill plant were higher than the expenditures. In S2 and S3, the sector costs, except for those from the demolition sector, were all negative. The costs of the landfill plants were the least, and the costs of the demolition sectors were the same. Since the distances from the demolition site to the market, recycling plant, and landfill plant were treated as the same, the cost of the transportation sector did not significantly change in any of the three scenarios. Because the quantity of landfilled waste was small, the costs of the landfill plants in S2 and S3 were minimal.

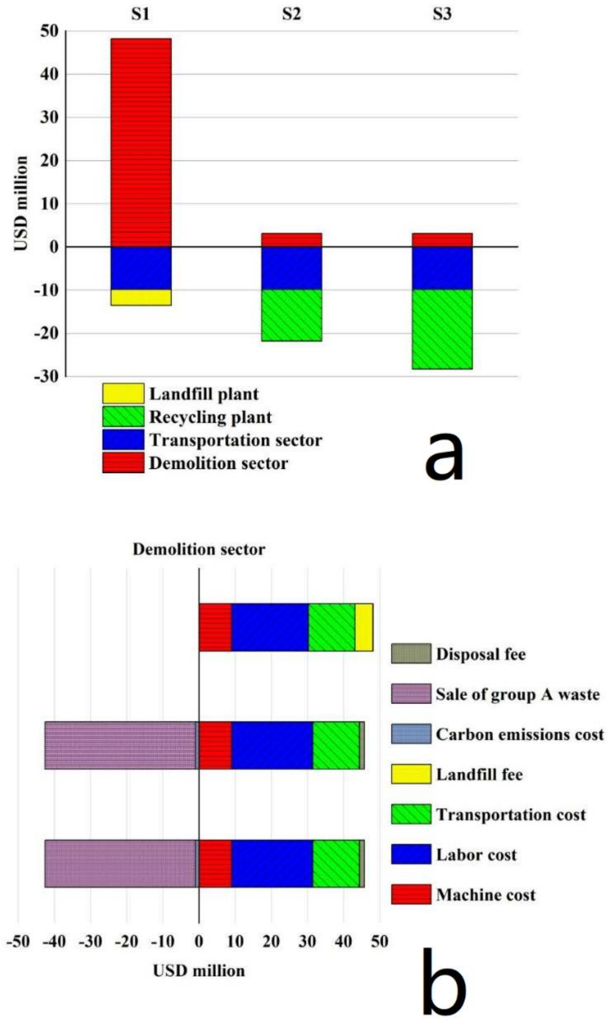

Figure 5. *Cont.*

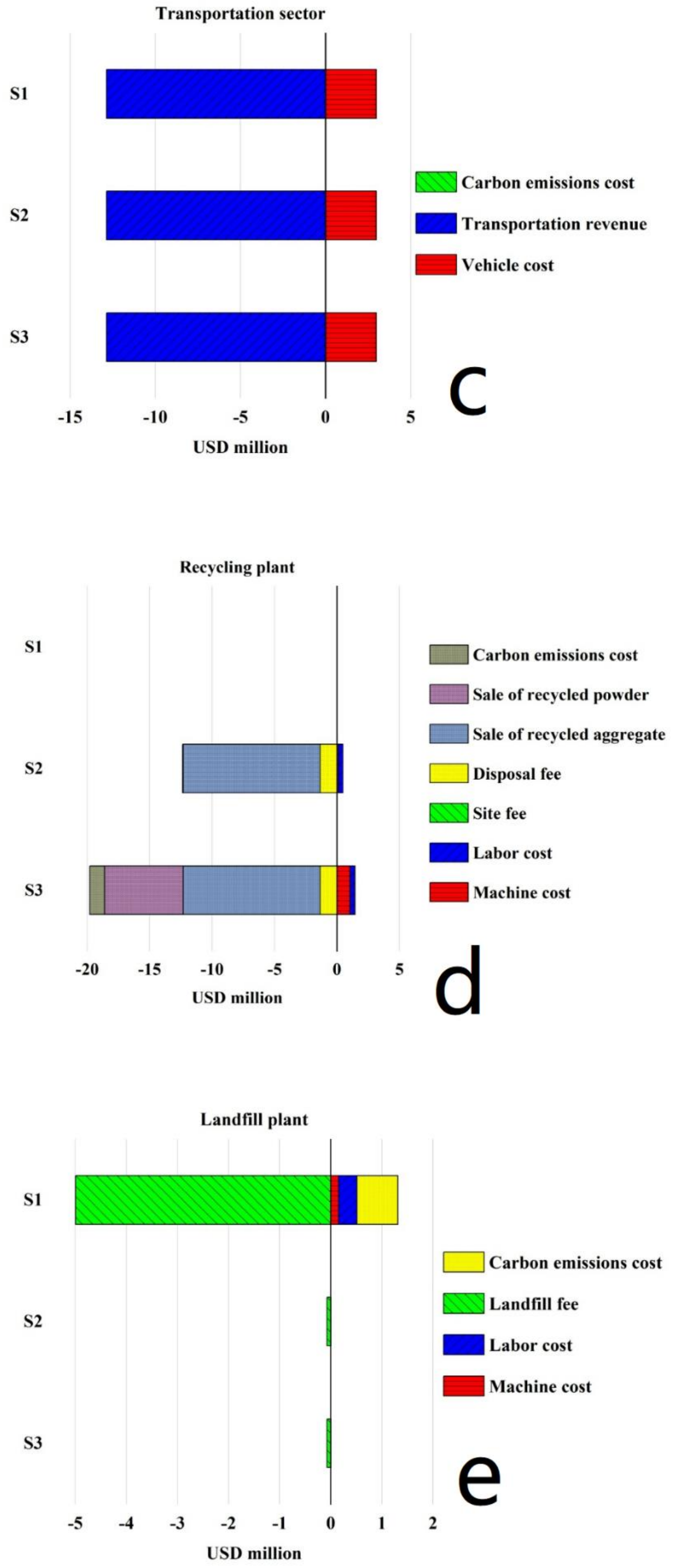

Figure 5. (**a**) Economic results; and breakdown of economic costs and benefits of (**b**) demolition sector. Breakdown of economic costs and benefits of (**c**) transportation sector; (**d**) recycling plant; and (**e**) landfill plant.

As shown in Figure 5b, the total cost of the demolition sector in S1 was USD 48.216 million, with the labor costs (USD 21.306 million) being the highest, followed by the transportation costs (USD

12.857 million). The expenses resulting from S2 and S3 were the same as the income. Owing to the huge income generated by the sale of group A wastes, the total cost (USD 3.171 million) was greatly reduced compared to that of S1. Although recycling group A wastes generates income, it also causes an increase in labor, machine, and carbon emission costs; however, the increase is not notable. Moreover, since group A and B wastes were no longer landfilled, the landfill fees for S2 and S3 (USD 0.071 million) were also greatly reduced. It is worth noting that the carbon emission cost in S1 was positive (USD 0.044 million), but those in S2 and S3 were negative (USD −0.963 million), indicating that the carbon emission reduction caused by the recycling of group A waste has economic benefits.

As shown in Figure 5c, the total cost of the transportation sector did not change significantly in the three scenarios (USD –9.867 million). The revenue from the transportation sector (USD −12.857 million) was much higher than the vehicle cost (USD 2.973 million), while the carbon emission cost was very small (USD 0.017 million); thus, the total cost of the transportation sector was negative.

The economic results of the recycling plant are shown in Figure 5d. There was no use of the recycling plant in S1; hence, the revenue and expenditures were both zero. In S2, the total cost of the recycling plant was USD −11.888 million, indicating that the production of recycled aggregate can increase the profit for the recycling plant. The expenditures of the recycling plant in S2 were primarily the labor costs (USD 0.362 million). The lowest cost was the site fee (USD 0.011 million), and the machine cost (USD 0.105 million) was slightly higher than the site fee. The revenue from the sale of the recycled aggregate (USD 10.970 million) was the main income source for the recycling plant in S2. Although the revenue generated by carbon emission reduction was small (USD 0.051 million), it shows that the carbon emission reduction resulting from processing group B waste into recycled aggregate can bring economic benefits. Compared to S2, the recycled powder was produced in the recycling plant in S3; thus, the corresponding machine (USD 1.039 million) and labor costs (USD 0.384 million) were higher than those for S2. Although the machine and labor costs increased, the sale of recycled powder generated considerable economic benefits (USD 6.291 million). At the same time, the replacement of raw materials with recycled powder reduced large amounts of carbon emissions, with an economic benefit of USD 1.193 million, making the total cost of S3 (USD 18.365 million) lower than S2.

As shown in Figure 5e, the amount of landfill required varied greatly among the three scenarios, causing the landfill costs to differ. The highest expenditure in S1 was the carbon emission costs (USD 0.800 million), followed by labor (USD 0.363 million) and machine costs (USD 0.152 million). These expenditures were small compared to the landfill fees (USD −4.995 million); hence, the total cost of the landfill plant in S1 (USD −3.680 million) was negative. The total costs of the landfill plant in S2 and S3 (USD −0.063 million) were also negative; however, the highest expenditure was no longer the carbon emission cost (USD 0.001 million), but the labor costs (USD 0.005 million).

3.3.3. Environmental Sensitivity Analysis

Based on the LCA results for the three scenarios, the environmental sensitivity of this case was analyzed. In each scenario, each variable was individually changed by ±20% to determine the change in the magnitude of the final result (total carbon emissions of the scenario) (see Appendix F).

In S1, a chemical reaction change of 20% caused an 18.55% change in the final result. In S2, the recycling of group A waste (±20.21%) had the greatest impact on the final result. The final result in S3 was the most sensitive to the replacement of raw materials with recycled powder (±10.79%). The machine operation from the demolition sector, vehicle operation from the transportation sector, machine operation at the landfill plant, and chemical reactions all had varying degrees of impact on the three scenarios.

Figure 6 shows the sensitivity ratios for each scenario. It can be observed that the chemical reaction was the most sensitive factor in the total carbon emissions from S1; the most influential factor in the final result for S2 was the recycling of group A waste, and the most influential factor in the carbon emissions in S3 was the replacement of raw materials with recycled powder. The least sensitive factor in the three scenarios was the machine operation in the landfill plant.

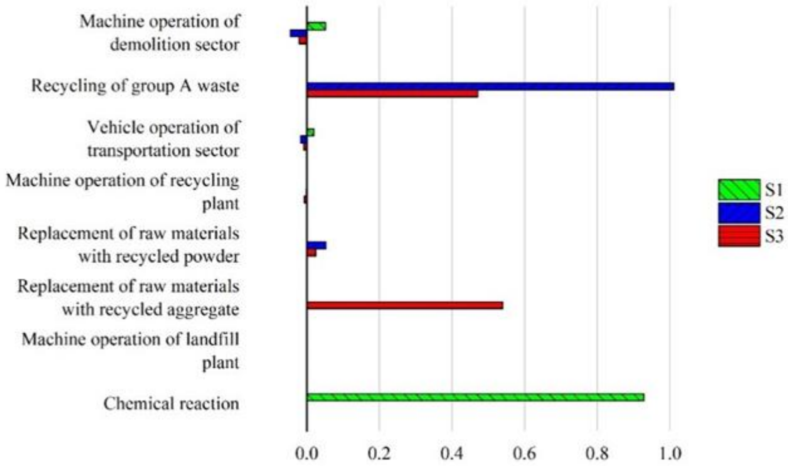

Figure 6. Sensitivity ratios (variation 20%).

3.3.4. Economic Sensitivity Analysis

Based on the LCC analysis of the three scenarios, this study conducted an economic sensitivity analysis for each sector. In each scenario, every relevant variable was individually changed by ±20% to determine the change in the final result (sector total cost). We divided the variation of the result by the variation of the variable to obtain the corresponding sensitivity ratio. As shown in Figure 7a, the total cost of the demolition sector in S1 was not sensitive to any of the variables; the labor costs (0.4419) had the greatest impact on the result, while the cost of carbon emissions (0.0009) had the least impact. The cost of the demolition sector in S2 was the same as that in S3; thus, the sensitivity ratio was the same. The sale of group A waste (−13.1407) had the greatest impact on the result, while the carbon emissions cost (0.0225) had the least impact.

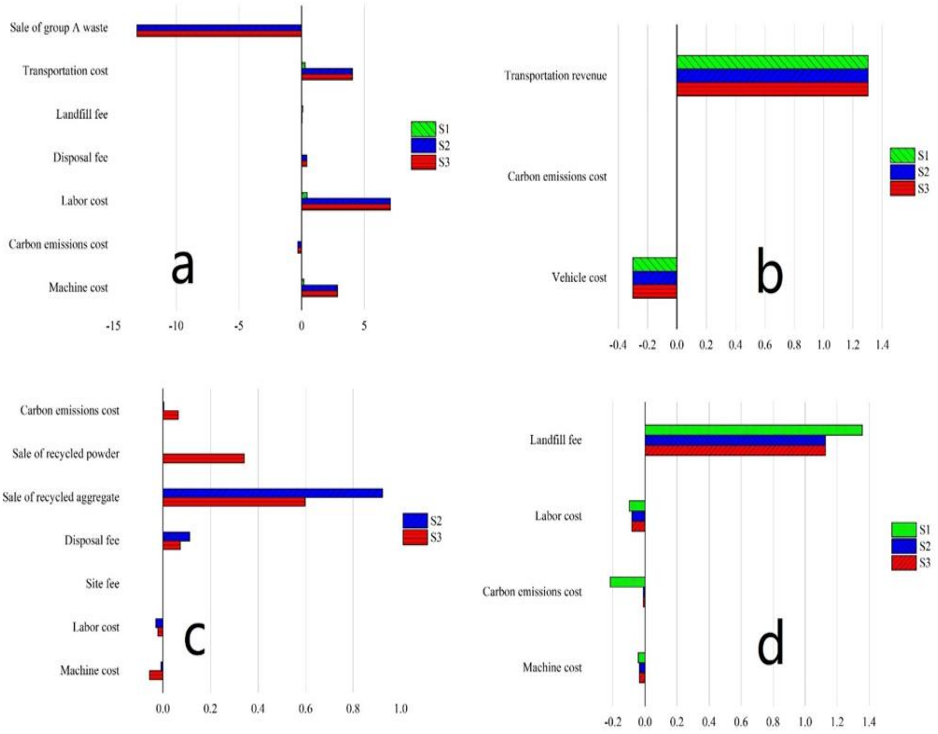

Figure 7. Economic sensitivity ratio of (**a**) demolition sector; (**b**) transportation sector; (**c**) recycling plant; and (**d**) landfill plant.

Figure 7b shows the economic sensitivity ratio of the transport sector. Since the distances from the demolition site to the market, recycling plant, and landfill plant were classed as the same, so were the sensitivity ratios of the three scenarios. The transportation revenue (1.3030) had the greatest impact on the total cost of the transportation sector, and the carbon emissions cost had the least impact (−0.0017).

Figure 7c shows the economic sensitivity ratio of the recycling plant. In S2, the revenue from the sale of recycled aggregate (0.9228) had the greatest impact on the result, while the site fee (−0.0009) had the least impact. The recycled aggregate revenue (0.5973) had the greatest impact on the results in S3, and the site fee had the least impact (−0.0006).

As shown in Figure 7d, the economic results of the landfill plant in S2 and S3 are the same; thus, the sensitivity ratios are also the same. The sensitivity ratio for S1 was slightly higher than those for S2 and S3, and the landfill revenue (1.3574) had the greatest impact on the result, while the machine costs (−0.0413) had the least impact. In each of the four sectors, the carbon emission costs had less impact on the final result than the other variables.

4. Discussion and Conclusions

In the process of urban development, a large amount of demolition waste is generated; thus, an economical and environmentally friendly approach to disposal is required. This study combined LCA and LCC to calculate the life cycle carbon emissions. We determined LCC of the demolition waste disposal process, analyzed the environmental and economic drivers of demolition waste management, and explored a new approach in the field of life cycle theory. This study also evaluated the advantages and disadvantages of three different disposal approaches for a demolition project in Guangzhou, China, and analyzed the impacts under different scenarios from both environmental and economic perspectives, providing a basis for the formulation of a demolition waste management policy and new ideas for the disposal of demolition waste.

Regarding the environment:

(1) The results of the LCA showed that the sale of group A waste can generate environmental benefits, and the production of recycled powder can greatly reduce carbon emissions. The recycling of group A waste reduced the overall carbon emissions; however, the results assumed that group A waste could completely replace raw materials. Therefore, if the wreck factor of waste is considered in the calculation, that is, a certain percentage of raw materials are replaced, the environmental benefits provided by recycling group A waste would likely be much less.

(2) The landfilling of plastics accounts for 56.64% of the total carbon emissions in S1, which is the most important source of carbon emissions in the demolition waste disposal process.

(3) Different from the subsequent production and processing that group A waste may need, the treatment of group B waste was fully considered. Therefore, the environmental benefits estimated for the recycling of group B waste are more consistent with the actual situation.

(4) The LCA results for S1 were the most sensitive to the chemical reactions in the landfill; for S2, the most sensitive variable was the replacement of raw materials with group A waste; and for S3, the most sensitive variable was the replacement of raw materials with recycled powder. It can be seen that different disposal approaches greatly affect sensitive factors in environmental impact assessments.

The results are in accordance with those of previous studies on recycled aggregate and powder. The production and use of recycled aggregate can reduce the environmental impacts caused by the production and use of natural aggregate [15]. By calculating the carbon emissions of the recycling plant, Coelho and Brito [18,32] found that the replacement of raw materials with recycled aggregate could generate environmental benefits. Blengini [33] conducted a life cycle assessment on a building in Italy and found that recycling steel and aggregate can provide environmental benefits. Although previous studies have suggested that recycling can provide environmental benefits, some materials have not been considered. Blengini [33] focused only on aggregate and steel, but not on aluminum, wood, glass, and plastic. The landfilling of plastic in this study generated 56.64% of the total carbon emissions of the scenario. Coelho and de Brito [9] focused only on the environmental benefits of recycled aggregate, not on the environmental benefits of processing waste into recycled powder.

The economic analysis emphasizes the following:

(1) Landfill fees are the main source of income for landfill plants;

(2) The revenue generated by the sale of group A waste is equivalent to 90.97% of the total expenditure of the demolition sector (the total cost of demolition sector, excluding the sale income of group A waste and carbon emissions cost).

(3) The main income of the recycling plant is the sale of recycled aggregate and recycled powder, rather than the disposal fee. Therefore, a lower disposal fee will produce more masonry waste, which can greatly increase the economic benefits of the recycling plant.

In this study, apart from the case in which there were extremely high carbon emissions, carbon emission costs did not have a significant impact on the costs for each sector. This may be the result of an immature carbon trading market and low carbon trading price. A significant difference between LCA and LCC is that because the environmental impact is static, the LCA need not take time into account; however, the economy is often dynamic, and time should be taken into account in the LCC. Because the duration of this study was very short and the dynamic economic analysis was complex, to maintain the consistency of the two theories, the time factor was not considered. This is a shortcoming of this study.

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

Appendix A

Table A1. List of notations.

Notation	Paraphrase	Unit
C_n	Total cost of sector n	USD
C_{Dn}	Direct cost of sector n	USD
C_{En}	Carbon emissions cost of sector n	USD
C_{Am}	Cost of activity m	USD
C_M	Machine cost	USD
C_L	Labor cost	USD
C_O	Other costs	USD
I	Income	USD
R_x	Unit time rental for machine x	USD/h
V_x	The efficiency of machine x	h/t
D_x	The workload of machine x	t
T	Manual working hours	h
S	Labor wage per unit time	USD/h
E_n	Carbon emissions of sector n	t
P	Carbon price	USD/t
E_{Am}	Carbon emissions from activity m	t
P_A	Average transaction price of carbon market	USD/t
E_M	Carbon emissions from machine operation	t
E_O	Carbon emissions from other factors	t
E_R	Emissions reductions	t
e_x	Consumption of energy e per unit time of machine x	kg
f_e	The carbon emissions factor of energy	e

Appendix B

Table A2. Main components of building demolition waste.

Waste Materials	Weight (t)
Total	1,258,324.36
Steel	57,600.41
Timber	14,399.68
Plastic	28,800.20
Aluminum	8358.44
Glass	2282.36
Brick	218,586.08
Concrete	682,692.60
Mortar	181,626.34
Ceramic tile	45,978.66
Mixed fragment	17,999.60

Appendix C

Table A3. Work efficiency, rate of energy consumption, and hourly cost of machines.

Sector	Machine	Work Efficiency	Unit	Energy Type	Energy Consumption Rate	Unit	Hourly Cost USD
Demolition sector	Rock drill	0.364608	h/m^2	Electricity	15.7	kwh/h	7.86
	Hydraulic hammer	0.043801	h/m^2	Diesel	18.9	kg/h	22.55
	Crawler bulldozer	0.025874	h/m^2	Diesel	17.8	kg/h	32.16
	Crawler excavator	0.027016	h/m^2	Diesel	17.8	kg/h	32.16
	Crawler hydraulic rock crusher	0.138606	h/m^2	Diesel	27.2	kg/h	33.08
Recycling plant	Electromagnetic separator	0.001707	h/t	Electricity	11.0	kwh/h	6.57
	Conveyor belt	0.001707	h/t	Electricity	15.0	kwh/h	5.72
	Vibration feeder	0.001913	h/t	Electricity	13.0	kwh/h	15.17
	Jaw crusher	0.001913	h/t	Electricity	87.0	kwh/h	2.17
	Horizontal screen	0.001913	h/t	Electricity	11.0	kwh/h	2.53
	Impact crusher	0.001913	h/t	Electricity	129.0	kwh/h	21.86
	Wind sorting machine	0.001913	h/t	Electricity	12.0	kwh/h	2.06
	Conveyor belt	0.001913	h/t	Electricity	22.5	kwh/h	3.33
	Spiral sand washer	0.012753	h/t	Electricity	5.5	kwh/h	1.67
	Dryer	0.012753	h/t	Electricity	160.0	kwh/h	23.40
	Powder mixer	0.012753	h/t	Electricity	29.5	kwh/h	4.53
	Centrifugal ball mill	0.012753	h/t	Electricity	2800.0	kwh/h	403.10
Landfill plant	Crawler bulldozer	0.004380	h/t	Diesel	17.8	kg/h	27.56

Data from the onsite survey in Guangzhou.

Appendix D

Table A4. Economic data.

Sector	Parameter		Unit
Demolition sector	Labor efficiency (S1)	8.28	h/m^2
	Labor efficiency (S2, S3)	8.75	h/m^2
	Labor wages	3.57	USD/h
	Transportation price	0.20	USD/t × km
	Price of recovered steel	350.16	USD/t
	Price of recovered timber	49.30	USD/t
	Price of recovered plastic	282.94	USD/t
	Price of recovered aluminum	1493.31	USD/t
	Price of recovered glass	68.59	USD/t
	Price of waste disposal	1.19	USD/t
	Price of waste landfill	3.97	USD/t
Transportation sector	Cost of the vehicle	0.43	USD/km

Table A4. *Cont.*

Sector	Parameter		Unit
Recycling plant	Labor efficiency (S2)	0.11	h/t
	Labor efficiency (S3)	0.12	h/t
	Labor wages	2.86	USD/h
	Rental unit price of the site	4.89	USD/h
	Price of recycled aggregate	11.43	USD/t
	Price of recycled powder	37.15	USD/t
Landfill plant	Labor efficiency	0.11	h/t
	Labor wages	2.57	USD/h
Carbon price		2.74	USD/t

Data from the onsite survey in Guangzhou.

Appendix E

Table A5. Transportation distance and energy consumption rate of transportation.

	Vehicle	Distance	Unit	Energy Type	Energy Consumption Rate	Unit
From the demolition site to the market	18-t freight lorry	50	km	Diesel	0.0117	kg/t × m
From the demolition site to the recycling plant	18-t freight lorry	50	km	Diesel	0.0117	kg/t × km
From the demolition site to the landfill plant	18-t freight lorry	50	km	Diesel	0.0117	kg/t × km

Data from the onsite survey in Guangzhou.

Appendix F

Table A6. Environmental sensitivity analysis (±20%).

Sector	Activities	S1	S2	S3
Demolition sector	Machine operation from the demolition sector	±1.03%	∓0.89%	∓0.42%
	Recycling of group A waste	/	±20.21%	±9.42%
Transportation sector	Vehicle operation from the transportation sector	±0.39%	∓0.34%	∓0.16%
Recycling plant	Machine operation at the recycling plant	/	∓0.02%	∓0.12%
	Replacement of raw materials with recycled aggregate	/	±1.05%	±0.49%
	Replacement of raw materials with recycled powder	/	/	±10.79%
Landfill plant	Machine operation at the landfill plant	±0.03%	∓0.00%	∓0.00%
	Chemical reaction	±18.55%	∓0.01%	∓0.01%

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