sustainability

Article

BIM-Based Assessment of the Environmental Effects of Various End-of-Life Scenarios for Buildings

Shuqiang Wang [1,2], Qingqing Wu [1,2,*] and Jinping Yu [1,2]

[1] School of Civil Engineering, Architecture and Environment, Hubei University of Technology, Wuhan 430068, China
[2] Key Laboratory of Intelligent Health Perception and Ecological Restoration of Rivers and Lakes, Ministry of Education, Hubei University of Technology, Wuhan 430068, China
* Correspondence: 102211004@hbut.edu.cn

Abstract: Accurately and rationally quantifying the environmental impact of construction and demolition waste (CDW) management is paramount, especially the environmental impact of different waste disposals, and more effective policies should be implemented to manage CDW. However, previous research on CDW disposal has typically ignored the potential for energy recovery and focused on a single environmental impact category. Therefore, this study aims to develop a conceptual framework to assess the environmental impacts under different CDW management scenarios (including reuse, recycling, energy recovery, and landfill), quantifying the global warming potential and resource consumption impacts under different scenarios. This framework incorporates Building Information Modeling to accurately collect data for feedback to the Life Cycle Assessment. The results indicate that Scenario 3, which considers the circular economy strategy, efficiently reuses metals, plastics, glass, and wood, generates recycled aggregate from concrete and cement, recycles bricks and tiles, and uses the remaining waste for energy recovery. This CDW management scenario, which prioritizes reuse and recycling, is the most effective in mitigating carbon emissions, resulting in a reduction of 6.641×10^5 kg CO_2 eq. Moreover, it significantly conserves resources and prevents the energy consumption of 4.601×10^7 MJ. Among them, metal reuse saves 42.35% of resources, and plastic reuse saves 31.19% of resources. In addition, increasing the reuse rate and recovery rate can directly avoid carbon emissions and cumulative exergy consumption, effectively alleviating environmental issues. This study can provide new ideas for the treatment of CDW, which can provide a basis for the relevant government departments to formulate CDW management policies.

Keywords: construction and demolition waste; environmental impact; life cycle assessment; building information modeling

check for updates

Citation: Wang, S.; Wu, Q.; Yu, J. BIM-Based Assessment of the Environmental Effects of Various End-of-Life Scenarios for Buildings. *Sustainability* **2024**, *16*, 2980. https://doi.org/10.3390/su16072980

Academic Editors: Édgar Ricardo Oviedo-Ocaña and Viviana Sanchez-Torres

Received: 28 February 2024
Revised: 26 March 2024
Accepted: 29 March 2024
Published: 3 April 2024

1. Introduction

Construction and demolition waste (CDW) is a kind of solid waste that arises from construction sites and the total or partial demolition of buildings and infrastructure [1]. It consists mainly of various inert materials (such as concrete and bricks) and non-inert materials (such as wood and plastic) [2]. CDW may contain harmful elements, such as toxic heavy metals [3]. If CDW is not disposed of properly, it can cause serious environmental problems and safety dangers. Accelerated global urbanization and industrialization have led to a massive increase in CDW. Global CDW is estimated to increase from 12.7 billion tons to 27 billion tons by 2050 [4].

At present, CDW disposal methods mainly include reuse, recycling, incineration, and landfill [5,6]. Most countries, especially developing countries like China, India, and South Africa, are more likely to use landfills or even illegal dumping. Around 35% of CDW is landfilled globally [7]. This disposal solution will have a huge negative impact not only on the environment, but also on waste recyclable materials and energy. Therefore, this unsustainable disposal method needs to transition toward sustainable approaches to reduce its environmental impact. The concept of a circular economy (CE) is a sustainable development strategy aimed at increasing the efficiency of material and energy use through regenerative models, thereby reducing waste and emissions [8]. It depicts an economic system based on a business model that replaces the unsustainable linear economic model of take-make-consume-dispose with a sustainable circular pattern of take-make-consume -reuse-recycle [9]. The circular economy model aims to maintain the circulation of products and materials through efficient and intelligent reuse strategies, thereby decreasing reliance on virgin materials and mitigating negative environmental impacts [10]. In the context of a circular economy, C&D waste management strategies are extended from open-ended “3R” (reduce, reuse, and recycle) to narrowing, slowing, and closing material loops [11]. Using the concept of CE to handle CDW can lead to reductions in carbon emissions as well as minimizing wastage and consumption of resources.

The global annual production of CDW exceeds 10 billion tons [12], resulting in significant adverse environmental impacts. The relevant environmental impacts include greenhouse gas emissions, resource depletion, land degradation, and landfill exhaustion [13]. Global warming and excessive resource consumption pose a threat to the ecological environment and human health [14,15]. Global warming is the increase in temperature due to the continuous accumulation of the greenhouse effect. Relevant studies have demonstrated an approximately linear relationship between cumulative carbon emissions and global average temperature [16]. We used carbon emissions to represent the global warming potential category. For resource consumption, we adopted cumulative exergy consumption as its indicator. When compared to other resource accounting methods, the major advantage is the ability to weigh different energy and material resources in a scientifically sound way, bringing them onto one single scale and eliminating the fuel and feedstock discussion [17]. Therefore, we considered two environmental impact indicators, global warming potential and resource consumption, for environmental assessment under different CDW management scenarios.

The Life Cycle Assessment (LCA) is widely used to assess the environmental impact of a product or process during its life cycle and is more commonly used in waste effect assessment. For example, Zakerhosseini et al. [18] used LCA to evaluate the environmental impacts of four methods: demolition, transport, recycling, and landfills. It took into account multiple environmental impact indicators but did not consider the potential for energy recovery. Wang et al. [19] developed a conceptual framework using BIM and LCA to evaluate the carbon emissions of building demolition waste. However, they emphasized carbon emissions and did not consider other environmental impacts. Qiao et al. [20] conducted a LCA of three typical recycled products manufactured from CDW. The results indicated that recycled products from CDW could achieve significant carbon emissions reductions. Zhang et al. [21] assessed the environmental benefits of producing recycled aggregates from CDW. The results indicated that using CDW to produce recycled aggregates is environmentally feasible. However, they only considered a single waste management method. Some other studies have focused on the comparison of CDW management solutions. For example, Wu et al. [22] evaluated the carbon emissions generated under three typical construction waste management scenarios based on a simplified LCA approach. They found that waste recycling has lower carbon emissions than landfilling. Liu et al. [23] used LCA to compare the carbon emissions generated under three different waste disposal options in Guangzhou, China, and discovered that the production of recycled powder could significantly reduce carbon emissions. Wang et al. [24] developed a framework based on LCA to assess carbon emissions from the life cycle of demolition waste and found that metal waste has a significant environmental contribution. However, the studies above focused mainly on the impact of carbon emissions, ignoring other environmental impacts and the benefits of recycling energy. To fill these research gaps, we take into account the potential of energy recovery and focus on the environmental impacts of multiple indicators.

Several studies have also assessed the impact of CDW management on resource consumption. Dewulf et al. [17] quantified the consumption of resources for construction materials under three end-of-life management options. Hoque et al. [25] analyzed the resource consumption generated at CDW recovery rates of 6.5% and 80%, respectively. Huysman et al. [26] used resource consumption indicators to select the most appropriate plastic waste treatment option. The scholars mentioned above have a bias toward analyzing the environmental impact based on individual indicators such as resource consumption, lacking research on multi-indicator analyses. However, few studies have specifically conducted environmental impact assessments focusing on the two indicators of global warming potential and resource consumption at the end-of-life of buildings.

To enable an accurate assessment of the environmental impacts of CDW, it is a prerequisite that appropriate methods should be established to quantify CDW information, such as CDW type, CDW number, and CDW position [27]. Currently, there are limitations to obtaining CDW data information accurately and efficiently. For instance, the on-site direct measurement method entails conducting surveys on-site, involving direct measurements such as weighing or volumetric measurements [28], which are time-consuming, labor-intensive, and costly. The unit area coefficient estimation method calculates the total waste amount by multiplying the provided unit generation rate by the relevant quantity [29]. Nevertheless, due to variations among buildings, this method lacks precision. Estimation based on material inventory and flow is another approach. This method is commonly employed to quantify the inventory of waste materials, input and output flows within a specified area, and their dynamic changes over a period to estimate waste quantities. However, this method is solely applicable for estimating waste on a regional scale and may not effectively analyze demolition waste from individual buildings. Based on these issues, BIM provides an effective solution. Building Information Modeling (BIM) is an information management process throughout the life cycle of a building that focuses on collaborative use of semantically rich 3D building information models [30]. Based on BIM-based CDW data calculation, the quantity information of materials can be accurately, quickly, and systematically extracted from the BIM model and combined with waste indicators, thus solving the problems of complexity and inaccuracy in quantification in building and construction waste management [31]. The emergence of BIM aims to innovate building management and promote more sustainable practices in the built environment [32].

Some researchers have already used BIM to quantify the amount of CDW. For example, Bakchan et al. [33] proposed a multidimensional framework based on BIM for automatic estimation of construction waste, providing guidance for the application of construction waste management. Kim et al. [34] proposed a BIM-based framework that estimates demolition waste during the early design stage to achieve effective and simplified planning, treatment, and management. Xu et al. [35] proposed a method that uses BIM technology to accurately quantify the greenhouse gas emissions of CDW. These studies have all achieved accurate quantification of waste through BIM; therefore, it is effective to adopt BIM technology in the acquisition stage of CDW data in this paper, which can improve estimation efficiency and accuracy. Some studies have combined life cycle assessment with BIM. For example, Su et al. [36] designed a tool that can quickly quantify the amount of waste and assess its environmental impact. Wang et al. [24] developed a BIM-based life cycle assessment method that can be comprehensively applied to evaluate the environmental impact of various stages of the building life cycle. However, these studies lack environmental assessments for different CDW management scenarios. Therefore, it is necessary to study the environmental impact assessment of different CDW management scenarios.

This study aims to present a conceptual framework to assess the environmental impacts generated under different CDW management scenarios. First, we conducted accurate information estimation of CDW based on BIM and applied mathematical formulas to quantify the impact of indicators. Then, we established a lifecycle environmental assessment model for CDW by integrating LCA to evaluate the impacts of CDW management on global warming potential and resource consumption. Through comparison and analysis of actual cases, we developed three different CDW management scenarios in order to identify environmentally friendly management options. This provided new insights for developing effective measures for managing building demolition waste.

2. Methods

In this study, we employed an integrated approach combining LCA and BIM to establish a conceptual framework. By integrating various mathematical formulas, we developed a CDW life cycle environmental impact assessment model to evaluate the environmental effects of CDW management. The overall conceptual framework is shown in Figure 1.

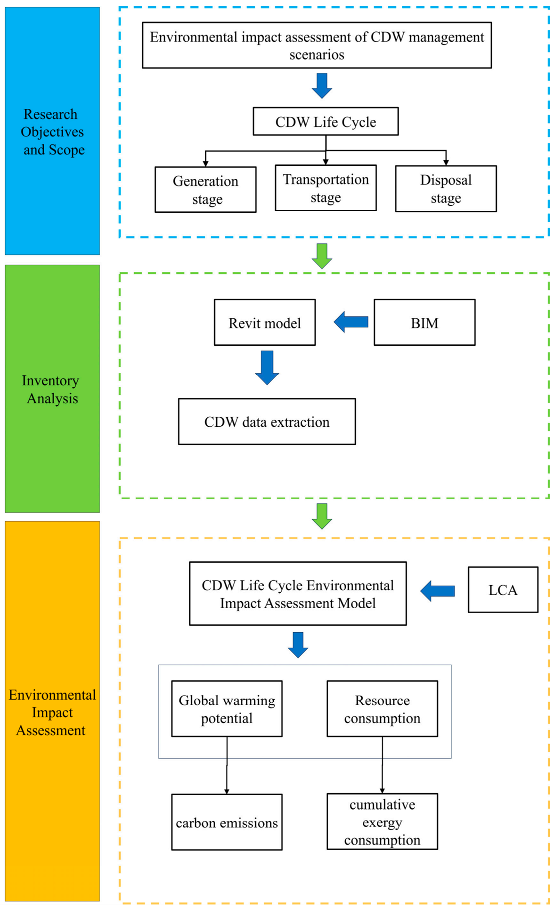

Figure 1. The overall conceptual framework.

2.1. Goal and Scope Definitions

The goal of this study is to identify the environmental impacts under different CDW management scenarios, considering two major impact categories: global warming and resource consumption. The relevant representative indicators are carbon emissions and cumulative exergy consumption. Figure 2 shows the scope of this study for the CDW life cycle, CDW from generation to final disposal. The main steps include waste collection and sorting, transportation, and disposal. In this study, the generated CDW collection was classified into three types of waste: Group A (metal, plastic, timber, and glass), Group B (concrete, cement, brick, and ceramic tile), and Group C (mixed fragment). The treatment of CDW varies depending on the management scenario.

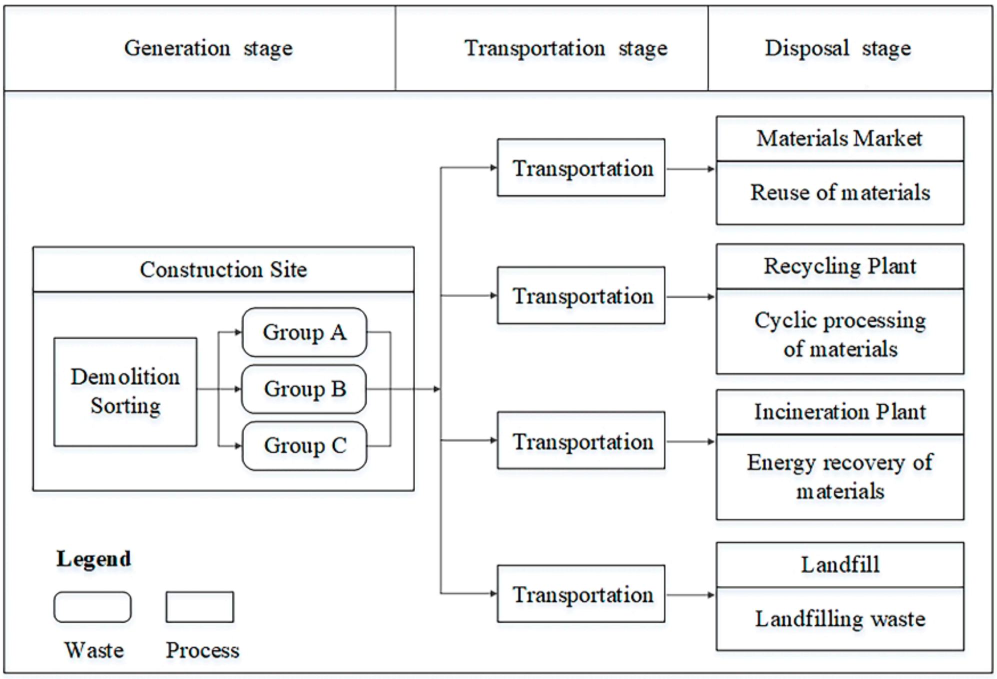

Figure 2. Life cycle stages of construction and demolition waste.

2.2. Inventory Analysis

In this stage, all data within the system need to be collected. The data information of CDW is the basis of LCA, so the type and quantity of CDW need to be accurately identified. Most current methods used to extract CDW information have proven to be time-consuming, inaccurate, and complex [35]. Studies have demonstrated the accuracy and adequacy of construction information and data obtained using BIM software and its ability to extract information on real material data. Therefore, this paper provides CDW data information through BIM. We use Revit 2016 software to create the architectural and structural model and the MEP model. The former simulates the main building structure and stores in-formation regarding the relevant components of the main building body (columns, walls, doors, etc.) and the corresponding building materials (concrete, bricks, glass, and other materials). The latter simulates the building plumbing and electrical wiring, with the corresponding materials made mainly of plastic. After the above models are created, their material types and volumes are extracted to form multiple component information schedules. They will be aggregated and classified to estimate the CDW quantity based on the amount of building elements as the CDW data source.

Other data include a range of carbon emission factors over the life cycle, machine efficiency, energy consumption factors, and unit leachate production. The specific data above were obtained from field surveys, literature reviews, and publicly available databases, but they will vary from one situation to another, and these data sources are discussed in the following sections.

2.3. Impact Assessment

This phase builds the CDW life cycle environmental assessment model. The carbon emissions reflect the global warming potential, and the cumulative exergy consumption reflects the resource consumption. The environmental assessment is carried out by analyzing the activities in the three stages of CDW generation, transportation, and disposal. The calculation of the indicators for each stage is as follows.

2.3.1. Carbon Emissions

The carbon footprint of buildings includes both operational carbon footprint and embodied carbon footprint [37]. Operational carbon refers to emissions generated from energy consumption during the operation of buildings [38]. Embodied carbon is the carbon emitted during the construction of buildings including production, construction, maintenance, and end of life stages [39]. The carbon emissions arising throughout the life cycle of CDW, categorized as embodied carbon emissions, primarily encompass two distinct aspects: one is the carbon emissions generated by various activities [40], and the other is the carbon emissions reduced through reuse, recycling, and energy recovery instead of raw materials [41], which bring environmental impacts and environmental benefits, respectively.

(1) Generation stage

This stage of the carbon emissions source is generated mainly by the operation of the machine, which is calculated as follows:

$$E_1 = \sum Q_a * V_a * e_a * f_e \quad (1)$$

where

E_1 is the carbon emissions from machine operation (unit: Kg CO_2 eq.),
Q_a is the amount of work done by machine a (unit: m^2 or t),
V_a is the work efficiency of machine a (unit: h/m^2 or h/t),
e_a is the energy consumption of the machine working per hour (unit: kg or kwh./h),
f_e is the carbon emission factor of unit energy (unit: Kg CO_2 eq./kg or kwh.).

(2) Transportation stage

In this stage, carbon emissions are determined according to the transportation volume, transportation distance, energy consumption rate, and carbon emission factor for the transportation process:

$$E_2 = \sum Qt_i * Dt_i * e_t * f_e \quad (2)$$

where

E_2 is the emission of vehicle operation (unit: Kg CO_2 eq.),
Qt_i is the amount of material i transported (unit: t),
Dt_i is the transportation distance of material i (unit: km),
e_t is the energy consumption of transporting one kg item per km (unit: kg/t·km),
f_e is the carbon emission factor of unit energy (unit: Kg CO_2 eq.).

(3) Disposal stage

Based on the "2006 IPCC national greenhouse gas inventories program", the carbon emissions are calculated as the activity value multiplied by the corresponding emission factor [29]. We used IPCC 2013 GWP 100a V1.01 to calculate the carbon emissions of raw material substitutes.

(1) Material market

In this phase, the CDW reuse treatment generates all environmental benefits, i.e., the reduction of carbon emissions through the substitution of raw materials:

$$E_3 = -\sum Qr_i * fr_i \quad (3)$$

where

E_3 is the carbon emission benefits from material reuse (unit: Kg CO_2 eq.);
Qr_i is the amount of replaced material i (unit: t);
fr_i is the unit carbon emission factor for replacing raw material i (unit: Kg CO_2 eq./t).

(2) Recycling plant

The treatment emissions of CDW should be related to the treatment amount and the emission factor of the corresponding unit. To calculate the carbon emissions of each type of CDW, emission factors under different types of CDW were selected for the CDW cycle processing. Meanwhile, through waste recycling, raw materials can be replaced by recycled materials, i.e., carbon emission benefits can be generated through recycling, with the following equation:

$$E_4 = \sum Qk_i * fk_i - Qk_i * fh_i \quad (4)$$

where

E_4 is the carbon emissions from recycling (unit: Kg CO_2 eq.);

Qk_i is the amount of recycled processed material i (unit: t);

fk_i is the unit carbon emission factor for recycled processed materials i (unit: Kg CO_2 eq./t);

fh_i is the unit carbon emission factor for replacing raw material i (unit: Kg CO_2 eq./t).

(3) Incineration plant

Carbon emissions are generated when the waste is incinerated, while the energy recovered from the waste can replace other fossil fuels, thus reducing carbon emissions and bringing environmental benefits, which can be expressed by the formula:

$$E_5 = Q_i * Y - Q_i * \frac{E_w}{E_c} * \theta \quad (5)$$

where

E_5 is the carbon emission of waste incineration (unit: Kg CO_2 eq.),

Q_i is the amount of waste burned (unit: kg),

E_w is the calorific value of waste (unit: KJ/kg),

E_c is the standard coal calorific value (unit: KJ/kg),

f_e is the carbon emission factor of unit energy (unit: Kg CO_2 eq.).

Y is the carbon emission per kg unit of waste (unit: Kg CO_2 eq./kg),

θ is the carbon emissions per kg of standard coal (unit: Kg CO_2 eq./kg).

(4) Landfill

The emission factors under different types of CDW are selected when CDW is carried out to landfills:

$$E_6 = \sum Ql_i * fl_i \quad (6)$$

where

E_6 is the carbon emissions from landfill (unit: Kg CO_2 eq.);

Ql_i is the amount of landfill material i (unit: t);

fl_i is the carbon emission factor for landfill material i (unit: Kg CO_2 eq./t).

2.3.2. Cumulative Exergy Consumption

The cumulative exergy consumption for disposal at each stage of the CDW life cycle is expressed as follows.

(1) Generation stage

This stage of cumulative exergy consumption includes the consumption of machinery during waste demolition and sorting:

$$CExC_d = \sum Qd_i * rd_i \quad (7)$$

where $CExC_d$ is the cumulative exergy consumption in the generation stage (unit: MJ), Qd_i is the amount of material i (unit: kg), and rd_i is the exergy consumption factors for material i in the generation stage (unit: MJ/kg).

(2) Transportation stage

The cumulative exergy consumption in this stage is generated during vehicle transportation:

$$CExC_t = \sum Qt_i * rt_i \quad (8)$$

where $CExC_t$ is the cumulative exergy consumption in the transportation stage (unit: MJ), Qt_i is the amount of material i (unit: kg), and rt_i is the exergy consumption factor for material i in the transportation stage (unit: MJ/kg).

(3) Disposal stage

In this stage, the cumulative exergy consumption is that generated by the different disposal scenarios:

$$CExC_m = \sum Qm_i * rm_i \tag{9}$$

where $CExC_m$ is the cumulative exergy consumption in the disposal stage (unit: MJ), Qm_i is the amount of material i (unit: kg), and rm_i is the exergy consumption factor for material i in the disposal stage (unit: MJ/kg).

At the same time, when people use reuse or recycling options instead of landfill options for CDW disposal, the original resource extraction is avoided, i.e., the avoided product can be fully quantified as net avoided cumulative energy consumption, and this equation is as follows [17]:

$$CExC_{net.av.} = CExC_{av} + CExC_{end-of-life\ disposal} - CExC_{recovery} \tag{10}$$

where

$CExC_{net.av.}$ is the net avoided cumulative exergy consumption (unit: MJ),

$CExC_{av}$ is to avoid the cumulative exergy consumption required to produce electricity and heat from fossil fuels (unit: MJ),

$CExC_{end-of-life\ disposal}$ is the cumulative exergy consumption required for the initial option to treat the waste (unit: MJ),

$CExC_{recovery}$ is some cumulative exergy consumption required for energy recovery from waste materials (unit: MJ).

2.4. Results and Interpretation

To make comparisons of environmental impacts, some scholars use weighting methods to obtain a single score indicator for LCA, which may help decision makers read and easily interpret LCA results. However, this study presents a comparison that does not assign different relative importance factors to impact categories. This aspect is aggravated by the many variables at stake, which may give rise to the higher or lower relative importance of certain factors over others: the ecological sensitivity of certain regions, human concerns about that region, stakeholders' interests/opinions, time constraints, and economic reasons, among others [42]. Therefore, this study considers the importance of all impact categories equally.

The decomposition method is used to calculate the respective results for each category of indicators, and, finally, the results obtained at each stage for each indicator are summed up to obtain the total. Therefore, we obtain the total CDW life cycle carbon emissions E, total cumulative exergy consumption C.

$$E = E_1 + E_2 + E_3 + E_4 + E_5 + E_6 \tag{11}$$

$$C = CExC_D + CExC_t + CExC_m \tag{12}$$

3. Case Study

3.1. Case Description

To validate the applicability and effectiveness of the framework built in this paper, a typical high-rise residential building in Dalian, China, was selected for analysis. Although this case specifically centers on high-rise residential buildings, the present study introduces a comprehensive research framework and methodology that are applicable to various other building types. This building was constructed in 2005 and was recently prepared for demolition due to the city's renewal program. The case project is a shear wall structure with a total construction area of 5876 square meters, which is a civil building. Its construction materials can represent most general civil construction requirements, such as common steel, concrete, glass, and timber.

3.2. Inventory Analysis

Acquisition of CDW data information. In this study, we employed Revit 2016 software to create a three-dimensional visualization model of the entire building, attaining a Level of Development (LOD) rating of LOD300 [43]. The model represents various elements as distinct systems, objects, or components and provides crucial details including quantity, size, shape, location, and orientation. Additionally, the model incorporates non-graphical data pertaining to material properties, parameters, and other attributes of the components. This comprehensive model serves as an efficient tool for cost estimation and construction coordination, enabling functionalities such as collision detection, construction scheduling, and visualization. By using established three-dimensional visualization models encompassing architecture, structure, and MEP systems, we extracted pertinent information pertaining to the building's primary components, including their types, quantities, material parameters, and other attributes (see Figure 3). The collated and summarized data are presented in Table 1.

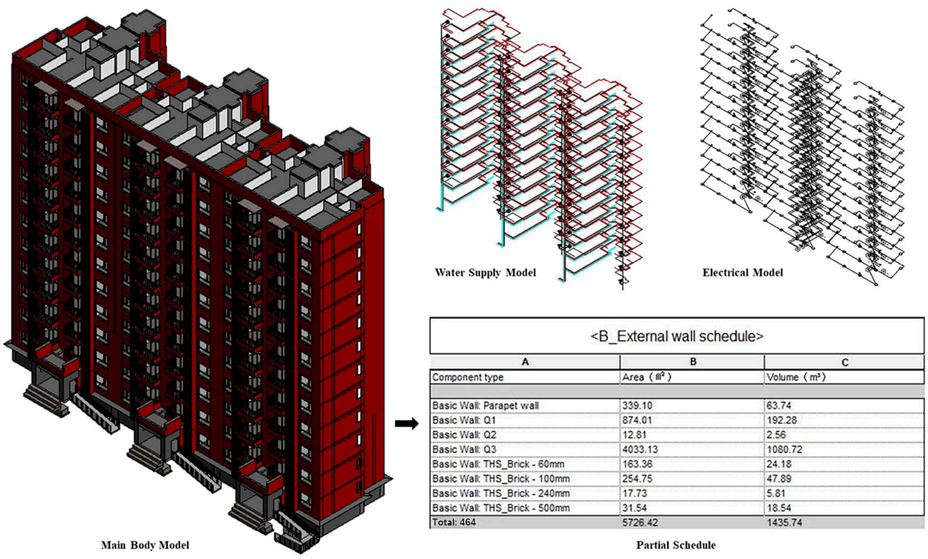

Figure 3. BIM visual models and partial schedule.

Table 1. CDW information schedule.

CDW Material	Volume (m³)	Density (t/m³)	Change Factor	Weight (t)
Group A				877.4
Steel	59.88	7.85	1	470.06
Aluminum	13.12	2.7	1.02	36.13
Plastic	133.55	1.6	1.1	235.05
Timber	159.89	0.7	1.05	117.52
Glass	7.10	2.5	1.05	18.64
Group B				9212.92
Concrete	2092.99	2.42	1.1	5571.54
Cement	617.61	2	1.2	1482.26
Brick	782.42	1.9	1.2	1783.89
Ceramic tile	126.34	2.7	1.1	375.23
Group C				146.89
Mixed fragment	94.16	1.3	1.2	146.89
Total				10,237.21

Through conducting a local market survey, we obtained the efficiency and energy consumption rates of the machinery required for the CDW generation phase (see Table 2). Given the actual distance in Dalian, we estimated the distance between the CDW demolition site and each disposal center to be approximately 30 km. Additionally, we sourced other inventory data, including the diesel carbon emission factors and electricity carbon emission factors for machine activities and transportation vehicles, from the IPCC 2013 GWP 100a V1.01 and the National Development and Reform Commission (NDRC), respectively (see Table 3). Furthermore, we retrieved the carbon emission factors for raw materials replaced by waste from the IPCC 2013 GWP 100a V1.01 (see Table 4). The carbon emission factors for disposal at recycling plants and landfills were derived from Shi et al. [44]. When calculating energy recovery, we obtained the calorific value of construction waste from Jin's research and the calorific value of standard coal from GBT2589-2020 [45,46]. Moreover, we extracted the disposal energy consumption coefficients for different waste stages from Dewulf [17]. The carbon emissions per unit of standard coal were sourced from the China Products Carbon Footprint Factors Database (CPCD) [47], whereas the carbon emissions per unit of waste incineration were based on Huang [48] (see Table 5).

Table 2. Work efficiency and energy consumption rates of machines.

Machine	Work Efficiency	Unit	Energy Type	Energy Consumption Rate	Unit	Data Source
Rock drill	0.355648	h/m^2	Electricity	16.1	kwh/h	onsite survey in Dalian
Hydraulic hammer	0.038396	h/m^2	Diesel	22.1	kg/h	
Crawler bulldozer	0.0266715	h/m^2	Diesel	17.3	kg/h	
Crawler excavator	0.025281	h/m^2	Diesel	17.3	kg/h	
Crawler hydraulic rock crusher	0.124016	h/m^2	Diesel	26.2	kg/h	

Table 3. Carbon emission factor of unit energy.

Energy Type	Carbon Emissions Factor	Unit	Source
Diesel	4.16015	kg CO_2 eq./kg	IPCC 2013 GWP 100a V1.01
Electricity	0.8357	kg CO_2 eq./kwh	NDRC, 2010

Table 4. Carbon emission factors of raw material reduction.

Waste Materials	Raw Materials Replaced	Carbon Emission Factors of Raw Material Reduction (kg CO_2 eq./t)	Source
Steel	Steel	2268.6477	IPCC 2013 GWP 100a V1.01
Aluminum	Aluminum	20,074.1686	
Plastic	Plastic	1866.6075	
Timber	Timber	919.2599	
Glass	Glass	1166.5981	
Masonry material waste	Natural coarse aggregate	2.4250	
Mixed fragment	-	-	

Table 5. Calorific value of materials and carbon emissions per unit of material.

Type	Unit	Numerical Value
Calorific value of construction waste	KJ/kg	5000 [1]
Calorific value of standard coal	KJ/kg	7000 [2]
Carbon emissions per standard coal	kg	2.493 [3]
Carbon emissions per unit of waste incineration	kg	0.61 [4]

[1] Data from Jin [45]. [2] Data from GBT2589-2020 [46]. [3] Data from CPCD [47]. [4] Data from Huang [48].

3.3. CDW Management Scenarios

As shown in Table 6, we have designed three CDW management scenarios. The first scenario represents the actual management situation in many Chinese cities currently. The second case considers the total flow from the landfill and minimizes downstream impacts due to the landfill. Third, we have developed a practical solution for efficient recycling based on circular economy principles.

Table 6. Waste management scenarios.

Material Type	Scenario 1	Scenario 2	Scenario 3
Group A			
Steel	Reuse	Reuse	Reuse
Aluminum	Reuse	Reuse	Reuse
Glass	Landfill	Reuse	Reuse
Plastic	Landfill	Incineration	Reuse
Timber	Landfill	Incineration	Reuse
Group B			
Concrete	Landfill	Recycle	Recycle
Cement	Landfill	Recycle	Recycle
Brick	Landfill	Recycle	Recycle
Ceramic tile	Landfill	Recycle	Recycle
Group C			
Mixed fragment	Landfill	Landfill	Incineration

3.3.1. Scenario 1

In China, the traditional CDW management method is linear way, using the "resource-product-waste" economic model, and the recycling and reuse rate of construction waste is less than 5% [6], and most of the CDW is simply landfilled. The only high-value waste that is reused or recycled is metals.

3.3.2. Scenario 2

This scenario is based on the open 3R strategy of the linear economy, taking into account the environmental impact of construction waste and debris management and controlling the landfill flow for final disposal. High-value materials like metals and glass are reused for sale, concrete, cement and bricks are recycled, timber and plastics are incinerated to recover energy, and the rest goes to landfills.

3.3.3. Scenario 3

In scenario 3, CDW management is based on a circular economy strategy. Different from the traditional linear economy of the past, the circular economy offers a new view of today's products as tomorrow's resources to create a virtual cycle in a world of limited resources [11]. The value of materials and products is preserved for the longest possible time in the life cycle, and at the end of the product's life cycle, the upgrade of recycled materials is carried out, which can be used repeatedly as a secondary resource. The implementation of reuse is considered one of the best waste management practices for the recirculation of materials in the CE model. It is preferred over recycling because of its lower energy use. Therefore, this scenario improves the reuse rate as much as possible, focusing on the upstream impact. Concerning the framework of the circular economy management model built by López et al. [49], metals, plastics, glass, and timber are treated for reuse, concrete and cement for recycled aggregates production, bricks and ceramic tiles for recycling, and the rest for energy recovery. This study assumes that materials sold in the market can completely replace the same amount of raw materials, and that materials recovered and processed in recycling plants can completely replace natural materials.

3.4. Calculation Results and Interpretation

Tables 7 and 8 show the carbon emissions and cumulative exergy consumption at different stages under the three management scenarios of CDW.

Table 7. Carbon emissions of the three waste management scenarios.

Stage	Scenario 1 (kg CO_2 eq.)	Scenario 2 (kg CO_2 eq.)	Scenario 3 (kg CO_2 eq.)
Generation stage	1.503×10^5	1.503×10^5	1.503×10^5
Transportation stage	1.520×10^4	1.520×10^4	1.520×10^4
Disposal stage	2.687×10^4	-3.003×10^5	-8.295×10^5
Materials market	-1.792×10^6	-1.813×10^6	-2.360×10^6
Recycling plant	0	1.703×10^6	1.703×10^6
Incineration plant	0	-4.128×10^5	-1.720×10^5
Landfill	1.819×10^6	2.233×10^5	0
Total	1.923×10^5	-1.348×10^5	-6.641×10^5

Table 8. Cumulative exergy consumption of the three waste management scenarios.

Stage	Scenario 1 (MJ)	Scenario 2 (MJ)	Scenario 3 (MJ)
Generation stage	1.167×10^6	1.167×10^6	1.167×10^6
Transportation stage	1.188×10^6	1.188×10^6	1.188×10^6
Disposal stage	2.676×10^6	3.166×10^6	3.082×10^5
Materials market	0	0	0
Recycling plant	0	2.509×10^5	2.509×10^5
Incineration plant	0	2.867×10^6	5.729×10^4
Landfill	2.676×10^6	4.847×10^4	0
Total	5.031×10^6	5.520×10^6	2.663×10^6

In Table 7, Scenario 1 produces the most carbon emissions (1.923×10^5 kg CO_2 eq.), followed by Scenario 2 (-1.348×10^5 kg CO_2 eq.) and Scenario 3 (-6.641×10^5 kg CO_2 eq.), where the negative carbon emissions indicate the environmental benefits of material reuse, recycling, and energy recovery. The carbon emissions generated by the scenarios are the same in the generation stage and the transportation stage. The generation stage produces the largest share of the carbon emissions in the CDW life cycle, reaching 1.503×10^5 kg CO_2 eq. The disposal stage includes the environmental impact of CDW disposal and the environmental benefits of CDW disposal. In Scenario 1, the largest contribution of carbon emissions is generated in the landfill with 1.819×10^6 kg CO_2 eq. Scenarios 2 and 3 have lower carbon emissions than Scenario 1 due to the environmental benefits associated with alternative raw materials and energy recovery. As the total landfill flow of CDW is considered in Scenario 2, the carbon emissions generated in the landfill are 1.596×10^5 kg CO_2 eq. less than those in Scenario 1, which brings a huge benefit. However, the carbon emissions of Scenario 2 are higher than Scenario 3 by 5.293×10^5 kg CO_2 eq. because Scenario 2 has not yet fully maximized the use of the material, and some waste is still in the landfill. In Scenario 3, we reuse and recycle materials as much as possible, and the recycled resources avoid the use of virgin materials. Therefore, in the disposal stage, the reuse of treated steel, aluminum, plastic, timber, and glass as substitutes for the corresponding raw materials in Scenario 3 brings environmental benefits of up to 2.360×10^6 kg CO_2 eq. It effectively provides a long life for the material and extends the resource value of CDW.

In Figure 4, the avoided carbon emissions from material reuse, recycling, and energy recovery under each scenario are presented. The results show that among the three waste management options, the reuse of materials achieves the best emission reductions. Meanwhile, among the three waste management scenarios, the CDW management scenario in the circular economy avoids the most carbon emissions (2.644×10^6 kg CO_2 eq.), saving 8.519 × 10^5 kg CO_2 eq. and 1.359 × 10^5 kg CO_2 eq. compared to Scenarios 1 and 2, respectively.

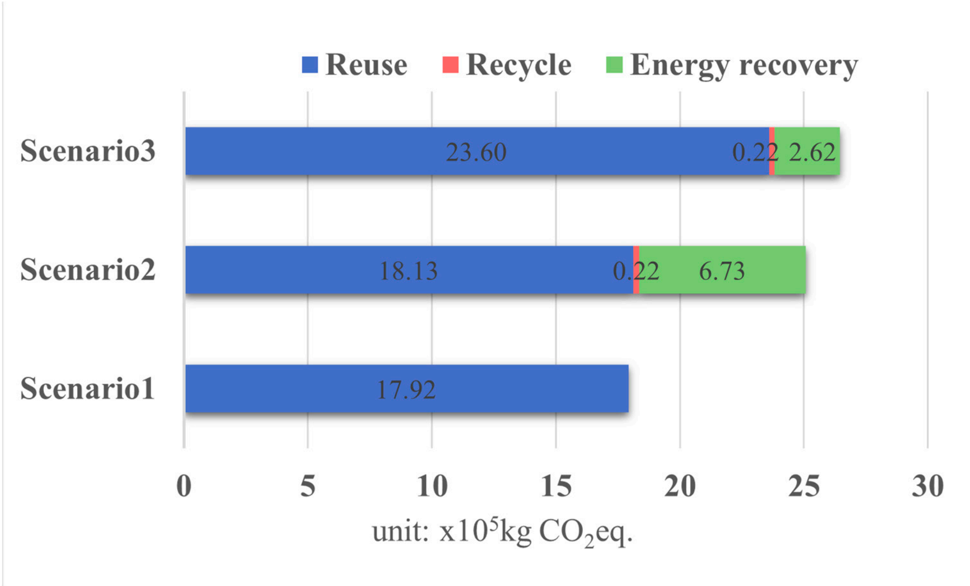

Figure 4. The avoided carbon emissions under different scenarios.

As seen in Table 8, the cumulative exergy consumption of the generation and transportation phases under each management scenario is the same. In the disposal phase, most of the CDW of Scenario 1 is disposed of in the landfill, so the cumulative exergy consumption is all generated at the landfill (2.676 × 10^6 MJ). The cumulative exergy consumption for Scenario 2 is higher than that of Scenario 1 by 4.89 × 10^5 MJ because energy recovery consumes more resources compared to landfill, but the former brings much greater resource savings than it consumes. Meanwhile, the CDW landfill in Scenario 2 still results in a cumulative exergy consumption of 4.847 × 10^4 MJ, as the conservation treatment has not been maximized. In contrast to the other scenarios, the maximum substitution of steel, aluminum, plastic, timber, and glass for the corresponding raw materials in Scenario 3 directly avoids the extraction of primary resources, i.e., the cumulative exergy consumption is zero. Scenario 3 has the lowest overall cumulative exergy consumption, with the main consumption coming from the recycling plant (2.509 × 10^5 MJ).

Table 9 shows the net avoided cumulative exergy consumption for different materials under the three management scenarios of CDW. The net avoided cumulative exergy consumption is always positive for all of the following disposal scenarios, indicating that either scenario results in net savings in raw resources. In Scenario 1, the reuse treatment of steel and aluminum saves 1.949 × 10^7 MJ, whereas the other materials have no savings because they are still disposed of in landfills. The energy saved in Scenario 2 is 1.2 times greater than in Scenario 1, due to the direct reduction in landfill volume and recycling of other materials, but there is still room for improvement in resource savings. Of the three scenarios, the third brings the most energy savings at 4.601 × 10^7 MJ. The most economical overall scenario includes the reuse of steel, aluminum, plastic, timber, and glass (saving 3.793 × 10^7 MJ), recycling of masonry materials such as concrete and masonry (saving 2.157 × 10^6 MJ), and energy recovery of mixed debris (saving 5.229 × 10^5 MJ), which can be seen as simple reuse makes for maximum resource savings.

Table 9. The net avoided cumulative exergy consumption.

Material Type	Scenario 1 (MJ)	Scenario 2 (MJ)	Scenario 3 (MJ)
Group A	1.949×10^7	2.136×10^7	3.793×10^7
Steel	1.233×10^7	1.233×10^7	1.233×10^7
Aluminum	7.155×10^6	7.155×10^6	7.155×10^6
Plastic	0	3.620×10^5	1.435×10^7
Timber	0	6.373×10^5	6.373×10^5
Glass	0	8.732×10^5	3.454×10^6
Group B	0	2.157×10^6	2.157×10^6
Concrete	0	1.003×10^6	1.003×10^6
Mixed debris	0	1.154×10^6	1.154×10^6
Group C	0	0	5.229×10^5
Mixed fragment	0	0	5.229×10^5
Total	1.949×10^7	2.352×10^7	4.601×10^7

4. Discussion

In this study, it can be found that maximizing reuse and recycling treatment under the circular economy strategy can bring the greatest environmental benefit rather than environmental impacts throughout the life cycle of CDW.

For the global warming potential category, the avoided reduction in carbon emissions at CDW disposal is five times greater than the sum of carbon emissions from the CDW generation and transport phases under the management approach of Scenario 3. This differs from Wu et al., who found that the deductible benefits of life-cycle carbon emissions from CDW, regardless of disposal measures, were not sufficient to offset the carbon emissions from the material embodied impact and transport phases [22]. This may be because it does not take energy recovery into account, whereas this study verified the benefits of energy recovery during CDW disposal.

For materials with high thermal potential (timber and plastics), Scenario 2 incineration disposal was performed, and the results showed that energy recovery can significantly reduce the carbon emissions generated by the raw materials, accounting for 26.83% of the carbon emissions saved by replacing them. The finding is also demonstrated by the study of electricity generation using wood chip pellets instead of coal [50].

Meanwhile, it can be found in the results of the carbon emissions from the different waste components that the share of CDW is only 0.35% of aluminum, the largest share of carbon emissions saved by replacing raw materials, accounting for 40.48%, 28.92%, and 27.44% of the carbon emissions avoided by various materials in Scenarios 1, 2, and 3, respectively. In contrast, concrete with a CDW share of 54.42% avoids only 0.15% of carbon emissions in the recycling of Scenario 3. This suggests that the environmental impact of various materials is not necessarily proportional to mass or volume, which is consistent with Wang et al.'s study [24].

For the resource consumption category, the transport process generates the largest contribution (46.61%), which is directly related to the mode of transport and the volume of transport. Moreover, simple disposal in landfills generates less resource consumption than energy recovery of plastics and timber in incineration plants, because energy recovery requires mechanical equipment to dispose of the waste, which generates more resource consumption. However, it should be noted that the raw resource consumption avoided by energy recovery can yield additional benefits. This is consistent with the study of Dewulfa et al., which found that if 1 kg of wood was recycled for energy, 7.43 MJ of resource consumption would be saved [17]. For the stone fraction, disposal at a recycling processing plant is approximately 10 times less resource-intensive than landfill disposal, and the former also has a greater potential for resource savings, with 2.157×10^6 MJ avoided when the stone is recycled.

Of the three scenarios, the disposal scenario of Scenario 3 brings the greatest resource savings. The overall resource savings from Scenario 3 are approximately 17 times greater than those required for the disposal solution, which demonstrates the benefits of a CDW management program based on a circular economy. In this scenario, most of the resource savings are related to metals (42.35%), followed by plastics (31.19%), but their mass share is only 4.9% and 2.3%. They have demonstrated that for energy-intensive materials, such as aluminum and plastics, more resource savings are added through reuse [25].

Based on BIM, this study has established an assessment framework. Despite the ongoing evolution of BIM and the challenges in predicting its future development [51], this assessment framework can serve as a reference for government departments in formulating policies for CDW management. The CDW management program under the principles of circular economy has demonstrated high environmental performance. The results show that the increase in reuse and recycling rate can directly avoid carbon emission and cumulative exergy consumption and effectively mitigate environmental problems. Therefore, government departments focus on the improvement of reuse and recycling rates, including recycling and energy recovery. In particular, the disposal of energy-intensive materials such as aluminum and plastics should be emphasized. The transition from Scenario 1 to Scenario 3 requires the active cooperation of various stakeholders (designers and constructors, etc.) so that the environmental impact of CDW can be reduced at source and the disposal of different waste types with minimal environmental impact can be achieved.

5. Conclusions

This study proposes a conceptual framework that combines LCA and BIM methods to quantitatively assess the environmental impacts caused by CDW management. Through a case study project, three different CDW management scenarios were created. This study fills a research gap in assessing the impact of CDW life-cycle management on the aspects of global warming potential and resource consumption in the circular economy. Comparing the three waste management scenarios, the environmental impact under Scenario 3 CDW management is the minimum. The main findings of this study are as follows:

(1) Under the circular economy strategy, the CDW management plan that maximizes reuse and recycle has the least environmental impact and can avoid the most carbon emissions and cumulative exergy consumption. Therefore, when formulating CDW management policies, relevant departments should give priority to the circular economy strategy, substitute secondary materials for raw materials as much as possible, and focus on improving the reuse rate and recycling rate.

(2) The environmental benefits brought by the recycling of various materials are not necessarily proportional to their quality or volume. Compared with other materials such as concrete, the environmental benefits of metal and plastic reuse are the most significant, with metal ranking first in terms of the total amount of resource savings, followed by plastic. The best management approach for these energy-intensive materials is reuse, as it requires the least amount of energy compared to material recovery. Therefore, CDW management plans should prioritize the reuse of metals and plastics to reduce the environmental impact caused by carbon emissions and resource consumption.

(3) The avoidance of original resource consumption through energy recovery can generate additional benefits, and its saving effect on original resources cannot be ignored. Therefore, it needs to be comprehensively considered in decision making. For different materials, the resource consumption and resource-saving potential during the recycling process vary. Therefore, when formulating CDW management policies, relevant departments should select the most suitable treatment method based on actual conditions.

6. Limitations and Future Research Directions

The proposed framework has limitations. This paper solely addresses the scenario of collecting and sorting materials directly at the construction site, disregarding the reality that many construction sites lack such capabilities during demolition activities. If we entertain the option of transporting materials to other processing plants for sorting, it will inevitably incur environmental repercussions. Furthermore, the assumption made in this study that materials available in the market can seamlessly substitute the same quantity of raw materials, and that materials reclaimed and processed in recycling facilities can fully supplant natural materials, represents an idealistic scenario. Therefore, the figures provided in our study for carbon emission reductions and net avoided cumulative exergy consumption should be regarded as the utmost potential.

In forthcoming research, the actual circumstances of diverse construction sites should be taken into account to refine the framework. Additionally, when considering buildings slated for demolition, the advantages of selective deconstruction should be considered during the demolition process to maximize the quality of materials and enhance the efficiency of recycling building materials and components.

Author Contributions: Conceptualization, Q.W. and J.Y.; methodology, J.Y.; software, Q.W. and J.Y.; validation, S.W., Q.W. and J.Y.; writing—original draft preparation, Q.W. and J.Y.; writing—review and editing, S.W.; visualization, Q.W. and J.Y.; supervision, S.W. All authors have read and agreed to the published version of the manuscript.

Funding: The study was financially supported by the Open Project Funding of Key Laboratory of Intelligent Health Perception and Ecological Restoration of Rivers and Lakes, Ministry of Education, Hubei University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

References

1. Ginga, C.P.; Ongpeng, J.M.C.; Daly, M.K.M. Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production. *Materials* **2020**, *13*, 2970. [CrossRef] [PubMed]
2. Menegaki, M.; Damigos, D. A Review on Current Situation and Challenges of Construction and Demolition Waste Management. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 8–15. [CrossRef]
3. Belayutham, S.; González, V.A.; Yiu, T.W. A Cleaner Production-Pollution Prevention Based Framework for Construction Site Induced Water Pollution. *J. Clean. Prod.* **2016**, *135*, 1363–1378. [CrossRef]
4. de Oliveira Andrade, J.J.; Possan, E.; Squiavon, J.Z.; Ortolan, T.L.P. Evaluation of Mechanical Properties and Carbonation of Mortars Produced with Construction and Demolition Waste. *Constr. Build. Mater.* **2018**, *161*, 70–83. [CrossRef]
5. Bocken, N.M.P.; de Pauw, I.; Bakker, C.; van der Grinten, B. Product Design and Business Model Strategies for a Circular Economy. *J. Ind. Prod. Eng.* **2016**, *33*, 308–320. [CrossRef]
6. Huang, B.; Wang, X.; Kua, H.; Geng, Y.; Bleischwitz, R.; Ren, J. Construction and Demolition Waste Management in China through the 3R Principle. *Resour. Conserv. Recycl.* **2018**, *129*, 36–44. [CrossRef]
7. Kabirifar, K.; Mojtahedi, M.; Wang, C.; Tam, V.W.Y. Construction and Demolition Waste Management Contributing Factors Coupled with Reduce, Reuse, and Recycle Strategies for Effective Waste Management: A Review. *J. Clean. Prod.* **2020**, *263*, 121265. [CrossRef]
8. Akanbi, L.A.; Oyedele, L.O.; Akinade, O.O.; Ajayi, A.O.; Davila Delgado, M.; Bilal, M.; Bello, S.A. Salvaging Building Materials in a Circular Economy: A BIM-Based Whole-Life Performance Estimator. *Resour. Conserv. Recycl.* **2018**, *129*, 175–186. [CrossRef]
9. Oliveira, M.; Miguel, M.; van Langen, S.K.; Ncube, A.; Zucaro, A.; Fiorentino, G.; Passaro, R.; Santagata, R.; Coleman, N.; Lowe, B.H.; et al. Circular Economy and the Transition to a Sustainable Society: Integrated Assessment Methods for a New Paradigm. *Circ. Econ. Sustain.* **2021**, *1*, 99–113. [CrossRef]
10. Ghaffar, S.H.; Burman, M.; Braimah, N. Pathways to Circular Construction: An Integrated Management of Construction and Demolition Waste for Resource Recovery. *J. Clean. Prod.* **2020**, *244*, 118710. [CrossRef]
11. Ma, W.; Hao, J.L.; Zhang, C.; Di Sarno, L.; Mannis, A. Evaluating Carbon Emissions of China's Waste Management Strategies for Building Refurbishment Projects: Contributing to a Circular Economy. *Environ. Sci. Pollut. Res.* **2023**, *30*, 8657–8671. [CrossRef] [PubMed]
12. Wu, H.; Zuo, J.; Zillante, G.; Wang, J.; Yuan, H. Status Quo and Future Directions of Construction and Demolition Waste Research: A Critical Review. *J. Clean. Prod.* **2019**, *240*, 118163. [CrossRef]
13. Ding, Z.; Wang, Y.; Zou, P.X.W. An Agent Based Environmental Impact Assessment of Building Demolition Waste Management: Conventional versus Green Management. *J. Clean. Prod.* **2016**, *133*, 1136–1153. [CrossRef]

14. Rossati, A. Global Warming and Its Health Impact. *Int. J. Occup. Environ. Med.* **2017**, *8*, 7–20. [CrossRef] [PubMed]
15. Wang, Y.; Wang, X.; Wang, H.; Zhang, X.; Zhong, Q.; Yue, Q.; Du, T.; Liang, S. Human Health and Ecosystem Impacts of China's Resource Extraction. *Sci. Total Environ.* **2022**, *847*, 157465. [CrossRef] [PubMed]
16. Frölicher, T.L.; Paynter, D.J. Extending the Relationship between Global Warming and Cumulative Carbon Emissions to Multi-Millennial Timescales. *Environ. Res. Lett.* **2015**, *10*, 075002. [CrossRef]
17. Dewulf, J.; Van der Vorst, G.; Versele, N.; Janssens, A.; Van Langenhove, H. Quantification of the Impact of the End-of-Life Scenario on the Overall Resource Consumption for a Dwelling House. *Resour. Conserv. Recycl.* **2009**, *53*, 231–236. [CrossRef]
18. Zakerhosseini, A.; Abdoli, M.A.; Molayzahedi, S.M.; Salmi, F.K. Life Cycle Assessment of Construction and Demolition Waste Management: A Case Study of Mashhad, Iran. *Environ. Dev. Sustain.* **2023**, 1–27. [CrossRef]
19. Wang, T.; Wang, J.; Wu, P.; Wang, J.; He, Q.; Wang, X. Estimating the Environmental Costs and Benefits of Demolition Waste Using Life Cycle Assessment and Willingness-to-Pay: A Case Study in Shenzhen. *J. Clean. Prod.* **2018**, *172*, 14–26. [CrossRef]
20. Qiao, L.; Tang, Y.; Li, Y.; Liu, M.; Yuan, X.; Wang, Q.; Ma, Q. Life Cycle Assessment of Three Typical Recycled Products from Construction and Demolition Waste. *J. Clean. Prod.* **2022**, *376*, 134139. [CrossRef]
21. Zhang, M.; Liu, X.; Kong, L. Evaluation of Carbon and Economic Benefits of Producing Recycled Aggregates from Construction and Demolition Waste. *J. Clean. Prod.* **2023**, *425*, 138946. [CrossRef]
22. Wu, H.; Duan, H.; Wang, J.; Wang, T.; Wang, X. Quantification of Carbon Emission of Construction Waste by Using Streamlined LCA: A Case Study of Shenzhen, China. *J. Mater. Cycles Waste Manag.* **2015**, *17*, 637–645. [CrossRef]
23. Liu, J.; Huang, Z.; Wang, X. Economic and Environmental Assessment of Carbon Emissions from Demolition Waste Based on LCA and LCC. *Sustainability* **2020**, *12*, 6683. [CrossRef]
24. Wang, J.; Wu, H.; Duan, H.; Zillante, G.; Zuo, J.; Yuan, H. Combining Life Cycle Assessment and Building Information Modelling to Account for Carbon Emission of Building Demolition Waste: A Case Study. *J. Clean. Prod.* **2018**, *172*, 3154–3166. [CrossRef]
25. Hoque, M.R.; Durany, X.G.; Sala, C.S.; Méndez, G.V.; Peiró, L.T.; Huguet, T.V. Energy Intensity of the Catalan Construction Sector. *J. Ind. Ecol.* **2012**, *16*, 699–709. [CrossRef]
26. Huysman, S.; De Schaepmeester, J.; Ragaert, K.; Dewulf, J.; De Meester, S. Performance Indicators for a Circular Economy: A Case Study on Post-Industrial Plastic Waste. *Resour. Conserv. Recycl.* **2017**, *120*, 46–54. [CrossRef]
27. Peplow, M. Enzymes Offer Waste-to-Energy Solution. *Science* **2017**, *355*, 1360–1361. [CrossRef]
28. Hoang, N.H.; Ishigaki, T.; Kubota, R.; Tong, T.K.; Nguyen, T.T.; Nguyen, H.G.; Yamada, M.; Kawamoto, K. Waste Generation, Composition, and Handling in Building-Related Construction and Demolition in Hanoi, Vietnam. *Waste Manag.* **2020**, *117*, 32–41. [CrossRef]
29. Hu, Q.; Liu, R.; Su, P.; Huang, J.; Peng, Y. Construction and Demolition Waste Generation Prediction and Spatiotemporal Analysis: A Case Study in Sichuan, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 41623–41643. [CrossRef]
30. Isikdag, U.; Underwood, J. *A Synopsis of the Handbook of Research on Building Information Modelling*; May: Salford, MA, USA, 1 January 2010.
31. Won, J.; Cheng, J.C.P. Identifying Potential Opportunities of Building Information Modeling for Construction and Demolition Waste Management and Minimization. *Autom. Constr.* **2017**, *79*, 3–18. [CrossRef]
32. Lu, Y.; Wu, Z.; Chang, R.; Li, Y. Building Information Modeling (BIM) for Green Buildings: A Critical Review and Future Directions. *Autom. Constr.* **2017**, *83*, 134–148. [CrossRef]
33. Bakchan, A.; Faust, K.M.; Leite, F. Seven-Dimensional Automated Construction Waste Quantification and Management Framework: Integration with Project and Site Planning. *Resour. Conserv. Recycl.* **2019**, *146*, 462–474. [CrossRef]
34. Kim, Y.-C.; Hong, W.-H.; Park, J.-W.; Cha, G.-W. An Estimation Framework for Building Information Modeling (BIM)-Based Demolition Waste by Type. *Waste Manag. Res.* **2017**, *35*, 1285–1295. [CrossRef] [PubMed]
35. Xu, J.; Shi, Y.; Xie, Y.; Zhao, S. A BIM-Based Construction and Demolition Waste Information Management System for Greenhouse Gas Quantification and Reduction. *J. Clean. Prod.* **2019**, *229*, 308–324. [CrossRef]
36. Su, S.; Li, S.; Ju, J.; Wang, Q.; Xu, Z. A Building Information Modeling-Based Tool for Estimating Building Demolition Waste and Evaluating Its Environmental Impacts. *Waste Manag.* **2021**, *134*, 159–169. [CrossRef] [PubMed]
37. De Wolf, C.; Cerezo, C.; Murtadhawi, Z.; Hajiah, A.; Al Mumin, A.; Ochsendorf, J.; Reinhart, C. Life Cycle Building Impact of a Middle Eastern Residential Neighborhood. *Energy* **2017**, *134*, 336–348. [CrossRef]
38. Azzouz, A.; Borchers, M.; Moreira, J.; Mavrogianni, A. Life Cycle Assessment of Energy Conservation Measures during Early Stage Office Building Design: A Case Study in London, UK. *Energy Build.* **2017**, *139*, 547–568. [CrossRef]
39. Brooks, M.; Abdellatif, M.; Alkhaddar, R. Application of Life Cycle Carbon Assessment for a Sustainable Building Design: A Case Study in the UK. *Int. J. Green Energy* **2021**, *18*, 351–362. [CrossRef]
40. Peng, Z.; Lu, W.; Webster, C.J. Quantifying the Embodied Carbon Saving Potential of Recycling Construction and Demolition Waste in the Greater Bay Area, China: Status Quo and Future Scenarios. *Sci. Total Environ.* **2021**, *792*, 148427. [CrossRef]
41. Zhao, Q.; Gao, W.; Su, Y.; Wang, T.; Wang, J. How Can C&D Waste Recycling Do a Carbon Emission Contribution for Construction Industry in Japan City? *Energy Build.* **2023**, *298*, 113538. [CrossRef]
42. Coelho, A.; de Brito, J. Influence of Construction and Demolition Waste Management on the Environmental Impact of Buildings. *Waste Manag.* **2012**, *32*, 532–541. [CrossRef] [PubMed]
43. Level of Development (LOD) Specification–BIM Forum. Available online: https://bimforum.org/resource/lod-level-of-development-lod-specification/ (accessed on 20 March 2024).

44. Shi, Y.; Xu, J. BIM-Based Information System for Econo-Enviro-Friendly End-of-Life Disposal of Construction and Demolition Waste. *Autom. Constr.* **2021**, *125*, 103611. [CrossRef]
45. Jin, N.; Tai, J.; Xu, B. Study on physical and chemical characteristics of waste from construction waste transfer stations in Shanghai. *Environ. Sustain. Dev.* **2020**, *45*, 68–71. [CrossRef]
46. General Rules for Calculation of the Comprehensive Energy Consumption GBT2589-2020. Available online: http://ft.panzhihua.gov.cn/zfxxgk/fdzdgknr_1/lzyj/zcwj/1949798.shtml (accessed on 20 March 2024).
47. CPCD, China Products Carbon Footprint Factors Database. Available online: https://lca.cityghg.com/ (accessed on 20 March 2024).
48. Huang, J.; Zhang, H.; Tan, Q.; Zhan, M.; Lin, X.; Li, X. Calculation of Carbon Emissions of a Small Scale Waste Pyrolysis-gasification Incineration Plant. *Environ. Sanit. Eng.* **2021**, *29*, 1–6. [CrossRef]
49. López Ruiz, L.A.; Roca Ramón, X.; Gassó Domingo, S. The Circular Economy in the Construction and Demolition Waste Sector—A Review and an Integrative Model Approach. *J. Clean. Prod.* **2020**, *248*, 119238. [CrossRef]
50. Hossain, M.d.U.; Leu, S.-Y.; Poon, C.S. Sustainability Analysis of Pelletized Bio-Fuel Derived from Recycled Wood Product Wastes in Hong Kong. *J. Clean. Prod.* **2016**, *113*, 400–410. [CrossRef]
51. Borkowski, A.S. Evolution of BIM: Epistemology, Genesis and Division into Periods. *J. Inf. Technol. Constr.* **2023**, *28*, 646–661. [CrossRef]