Evaluating carbon emissions of China's waste management strategies for building refurbishment projects: contributing to a circular economy

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Abstract

This study evaluates carbon emissions of construction and demolition (C&D) waste generated by building refurbishment, using a life cycle assessment approach through a case study project in China. Three waste management scenarios were developed for a building refurbishment project in the city of Suzhou. Scenario 1 is under the business-as-usual C&D waste management practice in China; scenario 2 is based on the open-ended 3R strategy, which focuses on the downstream impact of waste; and scenario 3 considers both the upstream and downstream impact of waste. The results reveal that the composition of the waste generated from building refurbishment projects is different from construction and demolition projects. In the life cycle of C&D waste management of building refurbishment projects, the refurbishment material stage generates the highest carbon emissions compared to the dismantlement, refurbishment construction, and refurbishment material end of life stages. Scenario 1 produces higher carbon emissions than scenario 2, but the difference is not significant in the whole life cycle of the building refurbishment project, whereas carbon emissions for scenario 3 are significantly less than both scenario 1 and scenario 2. The study finds the reason for this difference is that scenario 1 and scenario 2 are based on a linear economy that relies on unsustainable demand for raw materials, whereas scenario 3 is based on a circular economy that uses upcycled materials to substitute for raw materials and considers waste management from a cradle to cradle perspective. This study fills a research gap by evaluating carbon emissions of different waste management strategies for building refurbishment projects, which are expected to be an increasing portion of overall construction activity in China for the foreseeable future.

Key words

Building refurbishment, construction, demolition, C&D waste, management, 3R strategy, carbon emissions, life cycle assessment, circular economy, upcycle

1. Introduction

The building sector accounts for more than 30% of total carbon emissions globally (IEA 2019). In an effort to reduce this, and eventually achieve carbon neutrality (Hossain and Poon 2018), the European Commission and International Energy Agency have set a goal of refurbishing more than 80% of existing building stock to reduce energy consumption by 2050 (Barbiero and Grillenzoni 2019). Meanwhile, China, as one of the world's leading economies, is discouraging large scale building demolition and rebuild as a way of reducing up to 400 million tons of construction and demolition

(C&D) waste and the 10% of associated carbon emissions it is responsible for each year (CABR 2014). The Chinese government has put building refurbishment as a priority in its sustainable development strategy for the building sector. During the period of China's "13th Five-year plan", more than 600 million m^2 of buildings were refurbished by the end of 2020 (MOHURD 2017). It could be expected that building refurbishment activities are likely to be an increasing portion of overall construction for the foreseeable future. Although refurbishment has demonstrated its environmental benefit compared with demolition and rebuild, all building refurbishment projects generate waste. Due to rapid urbanization and large-scale urban renewal projects, China generates about 2 billion tons of C&D waste every year (Zheng et al. 2017), which is a critical problem due to the huge pressure it exerts on depleting landfills and its environmental impact (Bovea and Powell 2016). Extensive studies have been devoted to C&D waste management, but most focused on new construction and demolition projects rather than building refurbishment projects (Wu et al. 2019). As construction activity increases around world, the study of C&D waste from building refurbishment projects becomes ever more important.

1.1 Waste management of building refurbishment projects

The current literature on managing building refurbishment waste mainly focuses on the waste management practices of waste estimation and reduction. Li and Yang (2014) identified critical factors influencing waste management in office building refurbishment projects in Australia and analyzed the interrelationship between these factors. Through literature review and survey, Villoria Sáez et al. (2019) identified best waste management practices in four different phases of building refurbishment projects: design of dismantle, design of construction, execution of dismantle, and new construction. Sezer and Bosch-Sijtsema (2020) identified tensions and barriers between actors in building refurbishment projects in Sweden from a service ecosystem perspective in order to improve waste management practices in such projects. Hardie (2011) investigated the recycling of waste from building refurbishment projects. Cheng and Ma (2013) adopted building information modelling to estimate waste in demolition and refurbishment projects. Villoria Sáez et al. (2018) evaluated the waste generation rates for seven vertical envelope energy refurbishment measures. These studies identified different factors and waste management practices of building refurbishment projects, which are more complicated than construction and demolition projects since building refurbishment involves partial dismantlement and new construction as an integrated process. However, none of these studies focused on reducing the environmental impact of C&D waste of building refurbishment from a life cycle perspective. There is therefore a need for managing and evaluating the carbon emissions of waste in the life cycle of building refurbishment to reduce unnecessary emissions.

1.2 Carbon emission evaluation of the C&D waste

Efforts on evaluating environmental impact caused by C&D waste mainly focus on the downstream impact of C&D waste and the comparison of the different waste disposal scenarios including landfilling, recycling, and incineration. Penteado et al. (2016) evaluated six C&D waste management scenarios including integrated waste management method of landfill, recycling and use C&D waste as the road pavement material through a case study in Brazil. Hossain et al. (2017) compared the environmental impact of different waste sorting systems including on-site sorting, offsite sorting, and landfill in Hone Kong using LCA method. Wang et al. (2018) adopted LCA and BIM to evaluate carbon emissions of three different demolition waste treatment methods through a case study of a high rise residential building in China. Liu et al. (2020) further analyzed the environmental impact of three waste disposal scenarios in Guangzhou, China. However, few studies have fully recognized the upstream impact in the whole life cycle of C&D waste. This has also been advocated by Mesa et al. (2021). Although Wu et al. (2015) and Wang et al. (2019) extended their LCA system boundary to include the impact of the upstream material stage, they didn’t explore the benefits of using recycled materials to substitute the raw materials and the benefit of the recycling and energy recovery by incineration. In addition, limited attempt has been made to evaluate the carbon emissions of the C&D waste of the building refurbishment project from cradle to cradle (Ghose et al. 2017）. Therefore, this study has fully considered the downstream and upstream impact of the whole life cycle of C&D waste of the building refurbishment project.

1.3 C&D waste management transition from a linear economy to a circular economy

In order to tackle the problem of C&D waste, numerous studies have been conducted on C&D waste management. Faniran and Caban (1998) found that a typical approach to managing waste was to adopt a waste management hierarchy, as illustrated in Figure 1, with the environmental impact of C&D waste management in ascending order from high to low. The C&D waste management hierarchy is in line with the “3R” strategy of waste management, namely reduce, reuse, and recycle, which has been widely adopted in the field of C&D waste management (Peng et al. 1997). Many studies have adopted this hierarchy to investigate how to minimize the amount of C&D waste ending up as landfill.

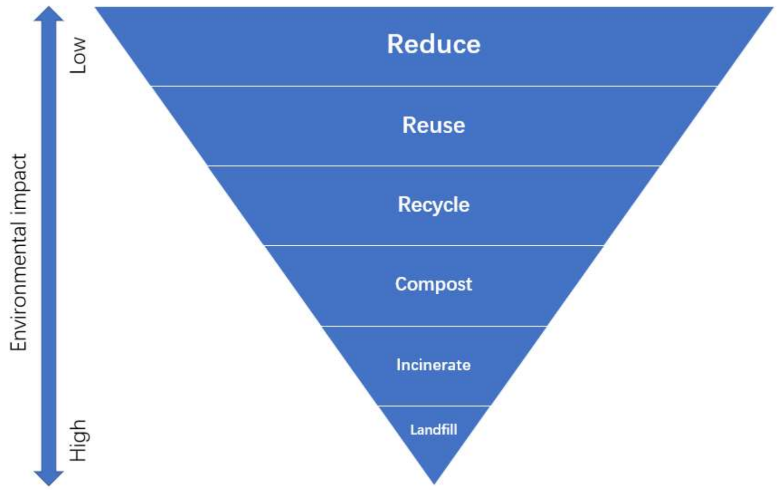

Figure 1. C&D waste management hierarchy (adopted from Peng et al. 1997)

The 3R strategy leads to an overall improvement but does not fundamentally solve the problem (Esa et al. 2017). There are still large amounts of C&D waste disposed of in landfills with a low recovery rate. Only about 30% of C&D waste is recovered globally (World Economic 2016). The overall C&D waste recovery rate in the European Union is still under the 70% recovery target by 2020 of the Waste Directive 2008/98/EC (López Ruiz et al. 2020). The recycling rate is around 70% in US, while only around 5% in China (Huang et al. 2018). The construction industry is currently considered to be a linear economy, expressed as "take-make-consume-dispose", which largely relies on the consumption of raw materials. Considering the growing demand for primary materials with the corresponding environmental disruptions, the construction industry is keen to implement new perspective and strategies, which are necessary to address many of today's challenges. In this context, the concept of the circular economy provides a view to consider today's products as tomorrow's resources in order to form a virtual cycle in a world of finite resources (Ellen MacArthur 2013). Transitioning from a linear economy to a circular economy has gained recognition in recent years as a solution to current C&D waste problems (Hao et al. 2020; Lei et al. 2020). There is therefore a need for strategies to achieve this transformation.

In the context of a circular economy, the resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops in a regenerative system (Geissdoerfer et al. 2017). The ultimate circularity concept is described by the Netherlands Environmental Assessment Agency (2017) as when a product is at the end of its life, its materials are recycled retaining its original quality so that the they can be used again in a similar product (Foster 2020). As a result, the discarded product produces new material and so no longer becomes waste. The concept of a circular economy in waste management not only minimizes waste and environmental impact in the material cycle, but, because of its emphasis on the redesign of processes and recycling of materials, it also contributes to more sustainable business models (Murray et al. 2017). The circular economy of C&D waste management achieves waste reduction, reuse, and recycling by narrowing, slowing, and closing resource circularity strategies without relying on the consumption of nonrenewable resources and the consequential degradation of the environment. It promotes reuse and upcycle within the construction industry to minimize material leakages in the conventional reuse and downcycling. This circular approach not only minimize the amount of C&D waste that ends up as landfill, but also reduces the demand for raw construction materials (Ginga et al. 2020; Hao et al. 2020). A linear approach verses a circular approach to waste management is illustrated in Figure 2.

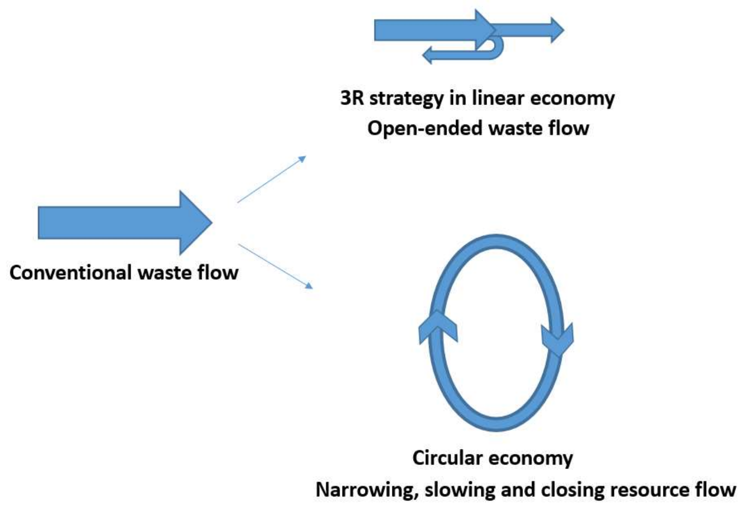

Figure 2. Linear vs. circular approach to waste management

In the context of a circular economy, C&D waste management strategies are extended from open-ended "3R" to narrowing, slowing, and closing material loops (Bocken et al. 2016; Franco 2019; Gallego-Schmid et al. 2020). Narrowing the loop means resource efficiency or narrowing resource flows, aimed at using fewer resources or reducing environmental impact per unit of product; slowing the loop means a prolonged and intensification of the utilization of products to retain the value over time; and closing the loop means the resource loop between the end of life and production is closed, resulting in a circular flow of resources by upcycling the used material.

Therefore, this study evaluates the carbon emissions of different waste management strategies for building refurbishment using a life cycle assessment approach through a case study project in Chin to fill the research gap of evaluating the carbon emissions of C&D waste in the life cycle of building refurbishment in the context of a circular economy, Three waste management scenarios are developed for a typical educational building refurbishment case study project in the city of Suzhou, China.

Scenario 1 is under the business as usually C&D waste management practice in China, scenario 2 is based on the open-ended 3R strategy that focus on the downstream impact of waste, and scenario 3 is based on a circular economy that considers both the upstream and downstream impact. These three scenarios are specifically chosen to demonstrate the impact of various waste management strategies on the reduction of carbon emissions for the building refurbishment case study project. This study provides valuable references for managing C&D waste and reducing carbon emissions of building refurbishment projects, which are expected to be an increasing portion of overall construction activities for the foreseeable future in the building sector.

2. Methodology

2.1 Scope and boundary

Life cycle assessment (LCA) is carried out in this study to evaluate the carbon emissions of C&D waste connected to building refurbishment based on ISO14040 (2006). The environmental impact of C&D waste should be taken into account before and after the generation of the waste in a life cycle building refurbishment strategy (Wang et al. 2019). The system boundary of C&D waste in the life cycle of building refurbishment is illustrated in Figure 3, which is based on EN 15978:2011 (CEN 2011) relating to the building refurbishment process. The system expansion is included in the system boundary of this study to account for the benefit of using secondary material in place of raw materials in production, as well as the benefit of reuse, recycle, and recovery of the waste (Salazar 2014). Therefore, the system boundary of the C&D waste includes four life cycle stages of the building refurbishment as illustrated in Figure 3, which are dismantlement, refurbishment material, refurbishment construction, and the refurbishment material at end of life.

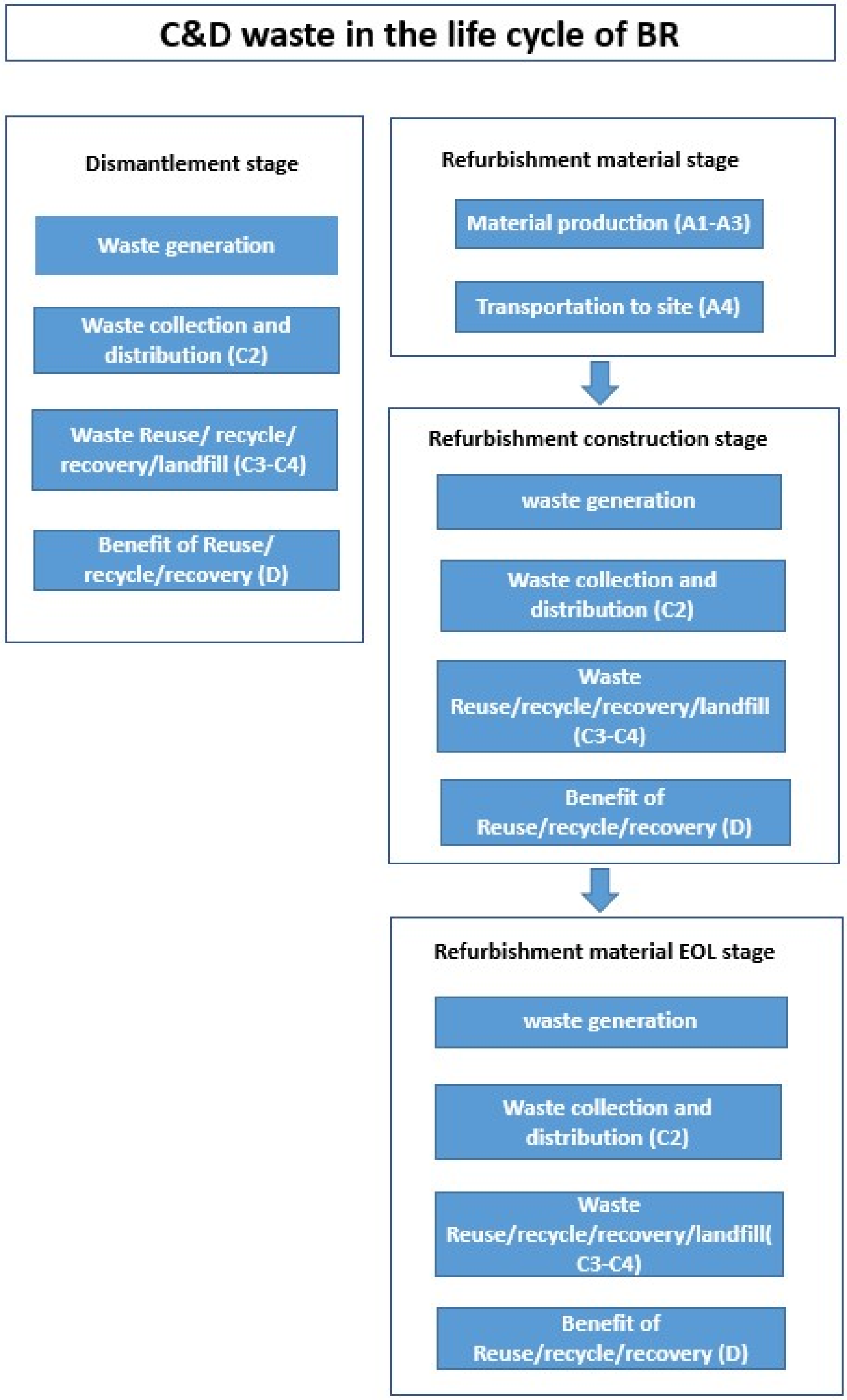

Figure 3. C&D waste in the building refurbishment (BR) life cycle
(Adapted from CEN, 2011; Vilches et al., 2017)

Dismantlement stage. The waste generated in dismantling the old building components is collected and distributed based on different waste disposal methods, including landfill, incineration, recycling, and reuse. Then the waste is processed by different disposal methods. The benefits of material reuse, recycle, and energy recovery are considered at this stage.

Refurbishment material stage. The upstream of the refurbishment material including raw material extraction and transportation to the factory is included in this stage. The refurbishment materials are produced and then transported from the manufacturer to the construction site.

Refurbishment construction stage. Waste is generated because of the different construction and installation processes and techniques. The generated waste is collected and distributed based on different waste disposal methods, including landfill, incineration, recycling, and reuse. Then the waste is processed by different disposal methods. The benefits of material reuse, recycle, and energy recovery are considered at this stage.

Refurbishment material at the end of life (EOL) stage. From a life cycle perspective, the EOL of refurbishment material is estimated from the refurbishment material used in the building refurbishment. The impact of material at EOL is affected by material selection and the waste disposal methods. The EOL waste is collected and distributed based on different waste disposal methods, including landfill, incineration, recycling, and reuse. Then the waste is processed by different disposal methods. The benefits of material reuse, recycle, and energy recovery are considered at this stage.

2.2 Life cycle inventory and impact assessment

Life cycle inventory involves the compilation and quantification of inputs and outputs for each process included within the system boundary. First-hand inventory data were collected from the case study project contractor including bill of quantities, design drawings, quantity of the waste, and waste composition of the building refurbishment project. Supplementary data was obtained from a site visit and interview with the project manager. The carbon emission calculation is based on the Chinese National Standard "Building carbon emission calculation standard (GB/T51366-2019)" (MOHURD 2019) and consistent with Intergovernmental Panel on Climate Change (IPCC) (2001) "Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories". The carbon emissions of waste management in building refurbishment are assessed by converting the various waste management emissions into CO_2 equivalent by using the CO_2 equivalent factor. The carbon emissions of the C&D waste in the whole life cycle of refurbishment are calculated by using the LCA software One Click LCA (Bionova, 2021), which is a standardized LCA tool complies with more than 30 standards worldwide including GB/T 51366-2019 and integrates global life cycle inventory databases. The CO_2equivalent factors are sourced from GB/T 51366-2019, global database "Ecoinvent 3.4" and "International EPD". The equations of carbon emission assessment derived from GB/T 51366-2019 can be expressed as follows,[W1]

Carbon emissions of refurbishment materials (MOHURD 2019)

$$C_{RM} = \sum_{i=1}^{n} W_{Mi} \times CEF_i \qquad \text{Eq. (1)}$$

where,

C_{RM}, Carbon emissions of refurbishment material, kg CO_2eq

W_{Mi}, Weight of material (i), t

CEF_i, Carbon equivalent factor of material (i), kg CO_2eq/t

Carbon emissions of refurbishment waste disposal (MOHURD 2019)

$$C_{EOL} = \sum_{i=1}^{n} W_{Wi} \times CEF_d \times P_d \qquad \text{Eq. (2)}$$

where,

C_{EOL}, Carbon emissions of EOL waste disposal, kg CO_2eq

W_{Wi}, Weight of waste (i), t

CEF_d, Carbon equivalent factor of waste disposal method (d), kg CO_2eq/ t

P_d , percentage of waste (i) which is processed by disposal method (d)[W用2]

Carbon emissions of material transportation (MOHURD 2019)

$$C_{MT} = \sum_{i=1}^{n} W_{Mi} \times D_i \times CEF_t \qquad \text{Eq. (3)}$$

where,

C_{MT}, Carbon emissions of material transportation, kg CO_2eq

W_{Mi}, Weight of the material (i), t

D_i, Transportation distance, km

CEF_t, Carbon equivalent factor of transportation method, kg CO_2eq/ (tkm)

Carbon emissions of waste transportation (MOHURD 2019)

$$C_{WT} = \sum_{i=1}^{n} W_{wi} \times D_i \times CEF_t \qquad \text{Eq. (4)}$$

where,

C_{WT}, Carbon emissions of waste transportation, kg CO_2eq

W_{Wi}, Weight of the waste (i), t

D_i, Transportation distance, km

CEF_t, Carbon equivalent factor of transportation method, kg CO_2e/ (tkm) [W3]

The equation of benefit of waste recycle is derived from Eq (1) as the raw material is replaced by the recycled material. Thus, the benefit of carbon emissions through waste recycle is equal to the carbon emissions of the replaced material, can be expressed as (MOHURD 2019),

$$C_{RB} = \sum_{i=1}^{n} W_{MRi} \times CEF_i \quad \text{Eq. (5)}$$

where,

C_{RB}, Benefit of carbon emissions through waste recycle, kg CO_2eq

W_{MRi}, Weight of material replaced by the recycled material (i), t

CEF_i, Carbon equivalent factor of replaced material (i), kg CO_2eq/t

The benefit of waste incineration is the energy generated through waste incineration. The amount of energy generated is converted to the carbon emissions (IPCC, 2001), the equation is expressed as (MOHURD 2019),

$$C_{IB} = E_{WI} \times CEF_P \quad \text{Eq. (6)}$$

where,

C_{IB}, Benefit of carbon emissions through waste incineration, kg CO_2eq

E_{WI}, Energy generated from waste incineration, kWh

CEF_P, Carbon equivalent factor of power plant, kg CO_2eq/kWh[W用4]

2.3 Case study project

The energy consumption of buildings has increased more than 200% in the past two decades in urban areas of China (Jiang et al. 2018; Ma et al. 2019). As the first energy efficiency standards for public buildings were not implemented in China until 2005, most of the existing buildings constructed in the middle of the twentieth century have very high energy consumption levels (MOHURD 2015). During China's "13th Five-Year Plan", more than 500 million square meters of buildings received an energy refurbishment (MOHURD 2017). The case study project is a typical educational building constructed about seven decades ago in the urban area of the city of Suzhou, China. The gross internal floor area of the case study project is 4829.08 m^2 and it received its energy refurbishment in 2019. The existing building envelop was obsolescent as its thermal property could not meet the current requirement of the energy efficiency standard, which is a common problem for old buildings. This study therefore focused on the envelope refurbishment measures for the building, and excluded the internal structure, equipment, and decoration.

The following envelope refurbishment measures, as illustrated in Table 1, were conducted in this building refurbishment project: for external walls, an expanded polystyrene (EPS) insulation layer was added; for the roof, the old waterproof layer was replaced and XPS insulation was added; and the existing windows were replaced with aluminum framed Low-e double glazed windows. These measures and materials are the mostly commonly used in building refurbishment and new construction in recent years in hot summer and cold winter climate regions of China (El-Darwish and Gomaa 2017; Ramli Sulong et al. 2019).

Table 1. Specifications of refurbishment measures for the building envelope

	Existing building	Refurbishment measures	Refurbishment area (m^2)
External wall	Brick wall without insulation	Add insulation layer	3737.12
External windows	Single-glazed aluminum framed window	Replace with low-e double glazed aluminum window	1313.4
Roof	Aged waterproof layer and without insulation	New waterproof layer Add insulation layer	1015.71

The data for this study were obtained from the project contractor, which included data from the bill of quantities and the design drawings, the quantity of waste, and the waste composition of the building refurbishment project. Supplementary data, including the different C&D waste disposal destinations, were obtained from site visits and an interview with the project manager. As transportation is mainly influenced by distance, which can vary greatly from project to project (Di Maria et al. 2018), transport distances are assumed to be equal for the same waste treatment method in this study. Inventories of the main waste materials from (i) dismantlement, (ii) refurbishment material and transportation, (iii) refurbishment construction, and (iv) transportations of the waste from site to the disposal destination are listed in Table 2, Table 3, Table 4, and Table 5 respectively.

Table 2. Inventory of the main waste materials from dismantlement

	Envelope	Waste material	Quantity	
Dismantlement waste from exiting building	**External wall**	Polymer cement mortar	82964.07	kg
	Window	Aluminum frame	6567	kg
		Window glass	1313.4	m^2
	Roof	Rigid layer and leveling layer: cement mortar	75162.54	kg
		Waterproof layer: EPDM	4062.84	kg

	Protection Layer: concrete	40.63	m^3

Dismantlement waste is the results of dismantling the parts of the existing building to be refurbished. The main dismantlement waste data were obtained from the as-built drawings and bill of quantities, including the dismantlement waste.

Table 3. Inventory of the refurbishment materials and transportation[W用5]

		Material	**Quantity**		**Transportation distance (km)**	**Transport type and capacity**
New material for refurbishment	**External wall**	Polymer cement mortar	50451.12	kg	57	Truck (30t) Diesel
		EPS insulation	3923.98	kg	123	Truck (30t) Diesel
	Window	Broken bridge aluminum frame	10507.2	kg	283	Truck (30t) Diesel
		Low-e double window glass	1313.4	m^2	283	Truck (30t) Diesel
	Roof	Rigid layer and leveling layer: Polymer cement mortar	54848.34	kg	57	Truck (30t) Diesel
		Waterproof layer: polyurethane-modified bitumen membrane	6906.83	kg	750	Truck (30t) Diesel
		Protection Layer: lightweight concrete	30.47	m^3	57	Truck (30t) Diesel
		Thermal insulation layer: XPS extruded polystyrene	2132.99	kg	123	Truck (30t) Diesel

Refurbishment materials are used to improve the existing building. The quantities of the refurbishment material data were obtained from the bill of quantities of the building refurbishment project and the construction drawings. The transportation distances were obtained by calculating the distance from the material manufactory's location to the building refurbishment site. Diesel trucks with a 30t capacity were used to transport the refurbishment material.

Table 4. Inventory of the main refurbishment construction waste

	Envelope	**Waste material**	**Waste Ratio**	**Quantity**		**Source**
Construction waste	External wall	Polymer cement mortar	2%	1009.02	kg	(DHURDJS 2014); Interview
		EPS insulation	4%	156.96	kg	(DHURDJS 2014); Interview
	Window	Broken bridge aluminum frame	5%	525.36	kg	(DHURDJS 2014); Interview
		Low-e double window glass	3%	39.4	m^2	(DHURDJS 2014); Interview
	Roof	Rigid layer and leveling layer: Polymer cement mortar	2%	1096.97	kg	(DHURDJS 2014); Interview
		waterproof layer: polyurethane-modified bitumen membrane	1%	69.07	kg	(DHURDJS 2014); Interview
		Protection Layer: lightweight concrete	1.5%	0.46	m^3	(DHURDJS 2014); Interview
		Thermal insulation layer: XPS extruded polystyrene	2%	42.65	kg	(DHURDJS 2014); Interview

The refurbishment construction waste is generated as the result of the refurbishment processes. In this case, the refurbishment construction waste data were not recorded. The on-site material wastage are estimated according to the method used in Li et al. (2013). Firstly, the material wastage ratios were obtained from the literature and verified through the interview with the project manager.

Table 5. Inventory of the waste material transported from site to disposal destination

Waste disposal	Transport type and capacity	Distance from the building refurbishment site (km)	Waste disposal destination
Landfill	Trucks (18 t) gasoline	40	Suzhou Wujiang Bachai landfill center
Inert waste recycling center	Trucks (18 t) gasoline	30	Suzhou Construction waste recycling center
Incineration center	Trucks (18 t) gasoline	25	Suzhou Qizishan waste incineration center
Aluminum recycling	Trucks (18 t) gasoline	24	Suzhou waste metal trading center
Glass recycling	Trucks (18 t) gasoline	27	Suzhou Luzhi resource recycling Center

According to the compositions of the C&D waste in this study, five waste disposal destinations in the city of Suzhou were identified: the landfill center, inert waste recycling center, incineration center, aluminum recycling center, and glass recycling center. Gasoline trucks with a capacity of 18t were used for the waste transportation.

2.4 Development of waste management scenarios

Three waste management scenarios were developed as shown in Table 6. Scenario 1 is under the 'business as usual' C&D waste management practice in China. Scenario 2 is based on the open-ended 3R strategy in the context of the linear economy that only considers the downstream impact of waste. Scenario 3 considers both the upstream and downstream impact of waste in the context of a circular economy. In this study, the evaluation in the scenarios analysis is constant and a fixed function of time, the dynamic and uncontrollable conditions are out of the scope of the analysis. [W用6]

Table 6. Waste management scenarios

	Type of material	Scenario 1	Scenario 2	Scenario 3

Waste in dismantlement stage	Cement-mortar	Landfill	Recycle	Recycle
	Aluminum frame	Recycle	Recycle	Recycle
	Glass	Landfill	Recycle	Recycle
	EPDM	Landfill	Incineration	Incineration
	Concrete	Landfill	Recycle	Recycle
New material in refurbishment material stage	Polymer cement-mortar	Raw material	Raw material	Cement with 50% GGBS
	EPS insulation	Raw material	Raw material	Recycled EPS
	Polyurethane-modified bitumen	Raw material	Raw material	Raw material
	Concrete	Raw material	Raw material	Recycled concrete
	XPS insulation	Raw material	Raw material	Raw material
	Aluminum frame	Raw material	Raw material	Recycled aluminum
	Low-e double glazing	Raw material	Raw material	Raw material
Waste in the refurbishment construction stage and refurbishment material EOL stage	Polymer cement-mortar	Landfill	Recycle	Recycle
	EPS foam	Landfill	Incineration	Incineration
	Polyurethane-modified bitumen membrane	Landfill	Recycle	Recycle
	Concrete	Landfill	Recycle	Recycle
	XPS	Landfill	Incineration	Incineration
	Aluminum frame	Recycle	Recycle	Recycle
	Low-e double glazing	Landfill	Recycle	Recycle

Senario1

Scenario 1 is under the business-as-usual C&D waste management practice in China. The majority of the C&D waste is disposed at landfills, only high value waste like metals is collected and recycled (Wu et al. 2015). Raw materials are currently the main source for construction material production in China's building industry. Therefore, in this case, in the dismantlement stage, aluminum frames are collected and transported to the recycling center, while other waste is disposed of at landfills. In the refurbishment material stage, the new material is produced from raw materials by a local manufacturer. In the construction stage and refurbishment material EOL stage, China's business as usual waste disposal practice is that only aluminum is recycled and other waste materials are disposed of at landfills.

Scenario 2

Scenario 2 is based on the open-ended 3R strategy of the linear economy that focuses on reducing the downstream impact of the waste generated in building refurbishment. It attempts to prevent the generated waste ending up as landfill. Instead, the intention is that generated waste in the dismantlement, construction, and EOL stages of building refurbishment will follow the 3R strategy. Therefore, for scenario 2 of this case study project, waste is further separated to be treated for recycling and incineration to improve the effectiveness of C&D waste management (Wu et al. 2020). [W用7]The inert waste aluminum, cement mortar, concrete, and glass are recycled, while plastic-based materials, including EPS, XPS, and EPDM, are incinerated for energy recovery at the end of its service life. The refurbishment material stage is the same as scenario 1, whereby local manufacturers produce new materials from raw materials.

Scenario 3

Scenario 3 is based on the circular economy strategy that considers both the upstream and downstream impact of waste from cradle to cradle. In this context, the waste is upcycled to retain the value of the product, resulting in the upcycled material being used as the material source for the new product. Therefore, besides waste generated in the dismantlement, construction, and EOL stages of building refurbishment recycled and recovered as in scenario 2, the refurbishment material is expected to contain secondary materials in scenario 3. Polymer cement-mortar with 50% ground granulated blast furnace slag (GGBS) is used in scenario 3. Aluminum frames are produced with 30% of recycled aluminum; EPS foam is produced with recycled polystyrene; Recycled aggregate and cement with 50% GGBS is used to produce the concrete in scenario 3. As scenario 3 mainly focuses on using secondary materials to substitute raw materials, it is also assuming that the transportation distance for both raw materials and secondary materials is the same.

3 Results and discussion

The results of the carbon emissions of C&D waste in different stages of the building refurbishment for the three scenarios are given in Table 7. As can be seen, the refurbishment material stage contributes the most to carbon emissions, much more than the dismantlement, refurbishment construction, and the refurbishment material EOL stages.

Table 7. Carbon emissions of the three waste management scenarios

Stage		**Scenario 1 (kg CO_2eq)**	**Scenario 2 (kg CO_2eq)**	**Scenario 3 (kg CO_2eq)**
Dismantlement stage	Waste transportation (C_12)	1137.93	852.35	852.35
	Waste processing and disposal (C_13-C_14)	715	8850	8850
	Benefit of waste reuse/recycle/recovery (D_1)	-54495	-80690	-80690
Refurbishment construction stage	Waste transportation (C_22)	18.74	14.03	14.03
	Waste processing and disposal (C_2 3- C_24)	44	483	483
	Benefit of waste reuse/recycle/recovery (D_2)	-4360	-5425	-5425
Refurbishment material stage	Material(A1-A3)	500795	500795	389715
	Transportation (A4)	2056.29	2056.29	2056.29
Refurbishment material EOL stage	Waste transportation (C_32)	909.39	677.02	677.02
	Waste processing and disposal (C_33-C_34)	574	12842	12842
	Benefit of waste reuse/recycle/recovery (D_3)	-87192	-121009	-121009
Total		360203.35	319445.69	208365.69

Scenario 1 has the highest total carbon emissions of 360203.35 kg CO_2eq, followed by 319445.69 kg CO_2eq for scenario 2, and 208365.69 kg CO_2eq for scenario 3. Although scenario 2 has less carbon emissions than scenario 1, the difference is not significant. Because of the benefit of waste recycle and energy recovery based on the 3R strategy, a total of 146047 kg CO_2eq, 207124 kg CO_2eq, and 207124 kg CO_2eq ($D_1 + D_2 + D_3$) of carbon emission are avoided for scenarios 1, 2, and 3 respectively. However, this could not contribute significantly enough to offset the total carbon emissions of the refurbishment material. Further improvement of effective C&D waste management strategies is needed (Wu et al. 2020).[W用8] In this study, the best strategy for reducing carbon emissions is in the material stage (A1-A3), during which the recycled materials are used as a substitute for raw materials. As for the scenario 3, 111080 kg CO_2eq of carbon emissions are saved in A1-A3 refurbishment material stage compared with senario1 and scenario 2. In the waste disposal stage (C3 to C4), which includes the impact of waste processing and waste disposal, scenario 2 and scenario 3 have higher carbon emissions than scenario 1. This is because plastic-based waste incineration, and concrete, glass, and cement waste recycling process consume energy. However, scenario 2 and scenario 3 have less total carbon emissions than scenario 1 because of the benefit of incineration energy recovery and material recycling. The benefit of incineration and recycling of scenario 2 are not as significant compared with scenario 1 because aluminum is also recycled in the current business as usual waste management practice. Therefore, to use an open-ended 3R strategy as in scenario 2 would not have much effect on reducing C&D waste carbon emissions. Considering the cradle-to-cradle impact of material and waste as in scenario 3, using upcycled materials as substitutes for raw materials significantly reduced the total carbon emissions of building refurbishment.

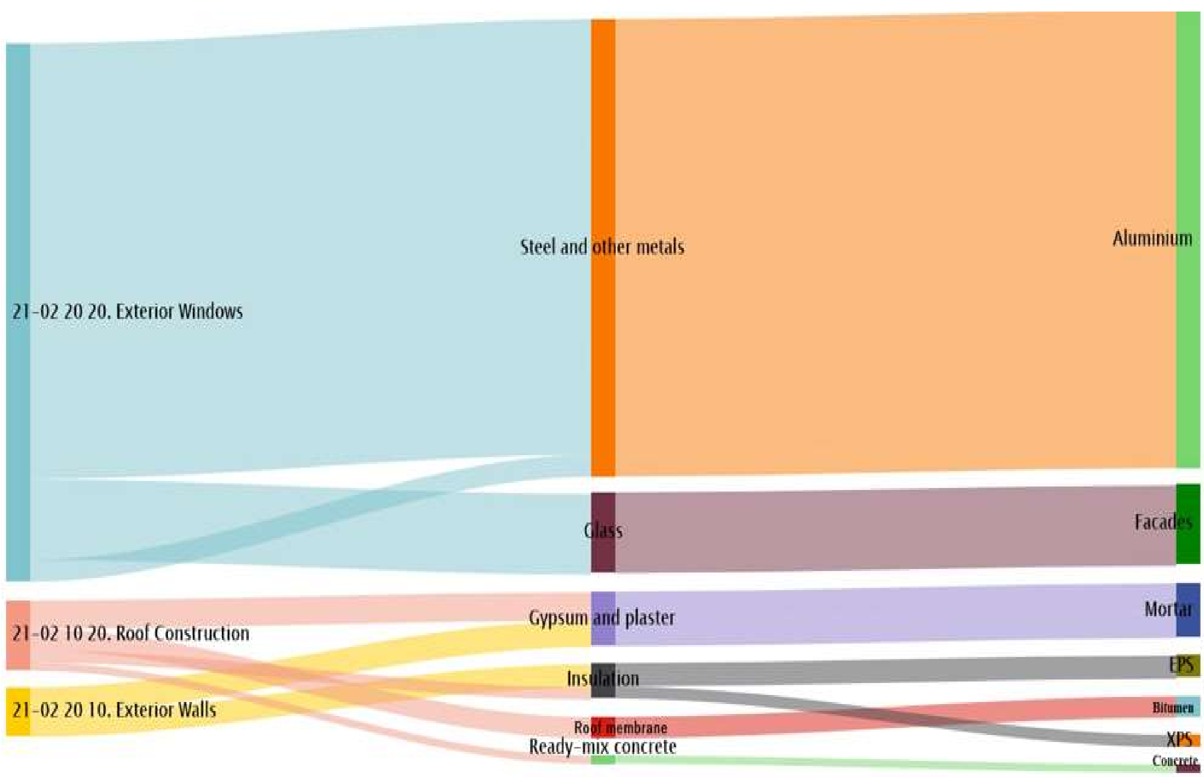

Figure 4. Carbon emissions of refurbishment material

The refurbishment material stage (A1-A3), which is the upstream of the generation of C&D waste in refurbishment, including raw material extraction, transport and production, produces significant embodied carbon emissions in the life cycle of building refurbishment. As can be seen from Figure

4, in terms of three main parts of the building envelop, the exterior windows contribute the highest carbon emissions than either the roof or exterior walls of this building refurbishment project. In terms of the refurbishment material, aluminum contributes the highest carbon emissions, followed by glass. Replacing old single white glass windows with low-e double glazed windows is one of the commonly used refurbishment measures to improve the energy performance of buildings in China. Increasing building refurbishment activities will demand more aluminum and glass materials and result in more aluminum and glass waste generation.

Secondary materials are used in scenario 3 for three main refurbishment materials as substitute for raw materials. The secondary material substitution ratio and avoided burdens are shown in Table 8. Recycled EPS board, recycled aluminum frame, and concrete with 40% recycled binder are used to avoid emissions from primary material extraction, transport, and production.

Table 8. Secondary material substitution ratio and avoided burdens

Secondary material	**Substitution ratio**	**Avoided burdens**
Recycled Aluminum	30% aluminum	Primary aluminum extraction, transport, and production
Recycled EPS	100% polystyrene	Styrene extraction, transport, and production
Recycled concrete	50% GGBS; 100% recycled aggregate	Cement extraction, transport, and production; Gravel extraction transport, and production
Cement-mortar with GGBS	50% GGBS	Cement extraction, transport, and production

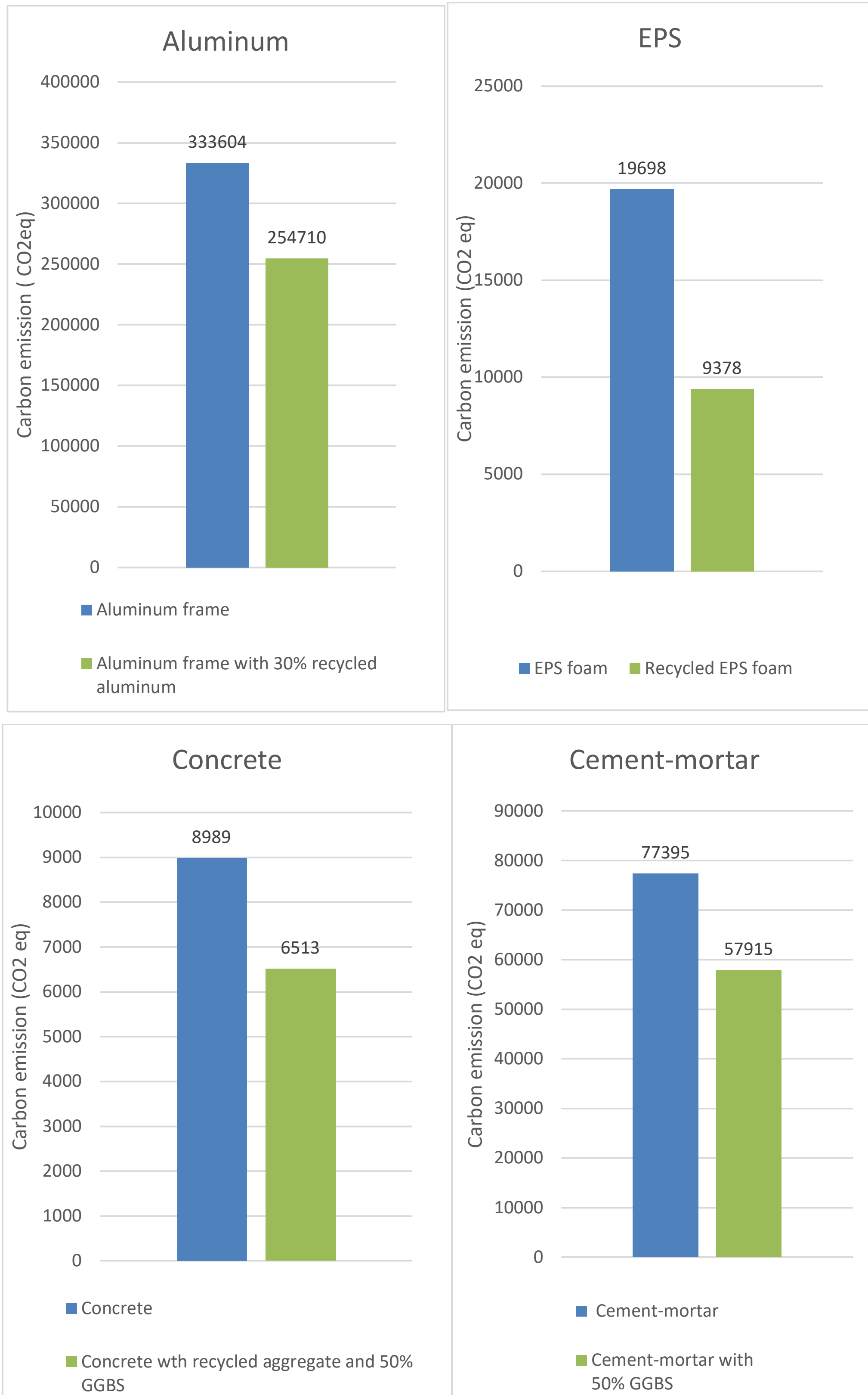

Figure 5. Carbon emission comparison between products with raw materials and secondary materials

As can be seen from Figure 5, carbon emissions are significantly reduced by using products made with recycled materials rather than using raw materials. The most significant amount of 78894 kg CO_2eq is reduced by using 30% recycled aluminium. The cement-mortar with 50% GGBS reduces up to 19480 kg CO_2eq carbon emission compared with using 100% cement-mortar. Recycled EPS saves 10320 kg CO_2eq of carbon emissions compared with EPS foam. As for concrete, recycled aggregate and 50% GGBS are used to reduce by 2476 kg CO_2eq. carbon emissions. As can be seen from the results that using seconday material effectively reduced the carbon emission even partial raw material is repalced. Especially for recycled aluminum, about 26% of carbon emission is avoided by replacing with 30% of recycled aluminum. Therefore, the upstream stages of design, planning and materials should not be neglected in the life cycle of building refurbishment waste management. The results of this study reveal that upcycled waste for raw material substitution could make a significant reduction in carbon emissions.

Table 9. Carbon emissions and benefit of C&D waste in different disposal methods

	landfill	**Incineration**	**Recycle**	**Benefit from incineration/ recycle (D)**	**Unit**
EPS	10	8104		-20510	kg CO_2eq
Concrete	459		54	-2471	kg CO_2eq
Bitumen	18		6	-320	kg CO_2eq
XPS	6	4405		-10934	kg CO_2eq
Glass	100		10	-496	kg CO_2eq
Aluminum			36	-146047	kg CO_2eq
EPDM	12	8391		-22183	kg CO_2eq
Cement	685		79.03	-4167	kg CO_2eq
Total	1290	20900	185.03	-207128	kg CO_2eq

Table 9 illustrates the carbon emissions and avoided carbon emissions of different waste disposal methods of the building refurbishment case study project. As can be seen from the results, of the three waste disposal methods, recycle produces less carbon emissions than landfill and incineration. Aluminum recycling avoids the most carbon emissions compared to the other waste management strategies. This is followed by incineration of EPS and XPS for energy recovery, while the incineration process consumes large amounts of energy, producing 8104 kg CO_2eq and 4405 kg CO_2eq respectively. Although the incineration process consumes large amounts of energy, the overall benefit from the energy recovered is more than it consumes, which avoids 19721 kg CO_2eq and 10720 kg CO_2eq respectively. Compared with the other materials, glass has the least benefits from recycling. As one of the main materials in building refurbishment projects, glass contributes significantly to carbon emissions in the material stage but produces little benefit from recycling. This result reveals the need for further studies on reducing the total carbon emissions of glass in the whole life cycle of building refurbishment in the context of a circular economy.

4 Conclusion

This study evaluated the carbon emissions of C&D waste in building refurbishment using a life cycle assessment approach through a case study project based on three scenarios for a typical building refurbishment project in the city of Suzhou, China. Scenario 1 is under the business-as-usual C&D waste management practice in China. Scenario 2 is based on the open-ended 3R strategies in the linear economy. Scenario 3 is in the context of a circular economy, which considers both the upstream and downstream impact of C&D waste in building refurbishment. This study fills the research gap of evaluating the carbon emissions of C&D waste in the life cycle of building refurbishment in the context of a circular economy. Comparing the carbon emissions of the three waste management scenarios, scenario 1 generates the highest total carbon emissions, with scenario 3 generating the least. Results from the study reveal that the reduction of carbon emissions from further use of an open-ended 3R strategy to recycle and recover more waste materials, as in scenario 2, would not significantly reduce carbon emissions from C&D waste over the life cycle of a building refurbishment project. Considering both the upstream and downstream impact of material waste in scenario 3, using upcycled material as a substitute for raw material could significantly reduce the total carbon emissions of a building refurbishment project. The results of this study provide valuable references for managing C&D waste and reducing carbon emissions of building refurbishment projects, which are expected to be an increasing portion of overall construction activities for the foreseeable future in the building sector.

The main findings from this study are as follows. As the main structure of the existing building remains intact in building refurbishment projects, the main C&D waste generated is different from construction and demolition projects. C&D waste from building refurbishment is generated mainly from the finish layer of the external walls and roof, insulation, window frames, and glass. The C&D waste composition in this case study project comprises mainly waste aluminum, glass, cement mortar, insulation, and waterproof membrane; concrete waste generated in building refurbishment projects is not as much as is generated in construction and demolition projects. As large-scale demolition and rebuild of existing buildings is discouraged by the Chinese government, C&D waste generated by building refurbishment projects is an increasing proportion of overall construction activities. In light of this finding and of government policy, it is suggested that future related research further explore the composition and the quantification of C&D waste generated by building refurbishment projects.

The refurbishment material stage generates the highest carbon emissions compared to the dismantlement, refurbishment construction, and the refurbishment material EOL stages. Among the three waste disposal methods of recycle, landfill, and incineration, recycle produces the least carbon emissions. Aluminum refurbishment materials contributes the highest carbon emissions, while recycling aluminum avoids more carbon emissions than the other waste management strategies. In contrast, glass generates the second largest amount of carbon emissions in its material stage but produces the least benefit from recycling. Whereas the open-ended 3R strategy is based on a linear economy, which relies on unsustainable increasing demand for raw materials, a circular economy strategy considers waste management from cradle to cradle to link the waste and material in a holistic waste management system that could solve the C&D waste problem.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The data and materials used during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions

Wenting Ma, conceptualization, data collection, results analysis, and writing; **Jian Li Hao**, conceptualization, supervision, review, and editing; **Cheng Zhang**, supervision; **Luigi Di Sarno**: supervision, review, and editing; **Adam Mannis**: supervision, review, and editing. All the authors contributed to the paper and approved the final version.

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