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Carbon Emissions Reduction of a Circular Architectural Practice: A Study on a Reversible Design Pavilion Using Recycled Materials

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Abstract: The construction industry, as a major consumer of resources and energy, accounts for about 40% of global carbon emissions. The concept of a circular economy (CE) is one effective means to address this issue. The entire lifecycle of a building includes: material production, construction, operation, and demolition. The production of building materials emits the largest proportion of carbon dioxide, followed by the operational phase, while construction (including demolition) has the smallest proportion. However, it is crucial to note the waste phase after demolition, where building materials are typically disposed of through incineration or landfill, leading to significant carbon emissions and environmental degradation. Therefore, carbon emissions generated during both the production and waste phases of the construction industry cannot be overlooked. This article employs a combined approach of practice and research, using the Circular Pavilion as a case study. From the design stage, reducing resource usage and carbon emissions are considered crucial factors. Reversible design, modularity, and the use of recycled materials are employed to reduce the emissions of “embodied carbon” and enhance material reuse. To validate the effectiveness of recycled materials in reducing greenhouse gas (GHG) emissions, this study calculates the material usage and carbon emissions during the production, transportation, and waste phases of the Circular Pavilion, Concrete Pavilion, and Steel Pavilion. The Circular Pavilion accounts for 34% and 3.5% of the total carbon emissions of the Concrete Pavilion and Steel Pavilion, respectively. In conclusion, the practical implementation of reversible design and recycled materials based on the concept of a circular economy is key to transitioning the construction industry from environmentally harmful impacts to eco-friendly practices. This establishes an effective method for resource reuse and carbon dioxide reduction in the construction sector, allowing waste resources to re-enter production and manufacturing processes, thereby reducing natural extraction, waste disposal, and energy consumption. Future applications of this method in the construction field involve establishing multidimensional composite design models and conducting feasibility assessments with upstream and downstream supply chains to support the realization of circular cities.

Keywords: circular economy; greenhouse gas; embodied carbon; reversible design; recycled materials; recycling for reuse



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1. Introduction

The extraction and use of natural resources promote the development of human science, technology, and economy, but human activities also have serious impacts on climate and ecosystems [1]. At the same time, humans’ extensive use of fossil fuels has also caused an increase in GHG emissions [2]. By 2025, it is estimated that GHG emissions

resulting from resource extraction will reach 60 billion tonnes [3]. The construction industry, which utilizes more than 50% of the world's natural resources, accounts for 37% of global GHG emissions. However, under current architectural design practices, only 3% to 4% of construction waste can be reused in buildings themselves [4]. Therefore, countries such as the Netherlands, France, and China have included the construction industry as a key sector for transformation in their CE policies. Europe, China, the United States, and others aim to achieve net-zero emissions by 2050, where CE development will play a crucial role [5]. China and the United States, among others, have strengthened their respective actions and jointly issued the "China–U.S. Joint Statement Addressing the Climate Crisis", showcasing global participation and efforts to reduce carbon emissions [6].

Sustainability has progressively become a significant goal for the development of human society. More and more researchers and industry practitioners are taking CE as an effective method to address resource wastage and GHG emissions in order to reverse the negative impact of the construction industry on the environment [7–9].

As one of the important tools for achieving sustainability, CE follows the principle of cradle-to-cradle [10]. The construction industry needs to consider reducing energy and raw material usage during the manufacturing process [11] and strive to use single materials as much as possible, reducing the mixing of different types of materials. This helps improve material reuse and slow down the physical degradation of materials [12]. By directly reusing through repair or renovation and indirectly reusing through returning materials to manufacturing for reprocessing or remanufacturing [13], the lifespan of materials can be extended, reducing material waste and GHG emissions. However, recycling methods such as using recycled materials as fuel or directly downgrading materials to fillers for foundations or concrete are not considered acceptable recycling methods [14]. In fact, glass can be safely melted into recycled glass through high-temperature melting [15]. Similarly, wood, polycarbonate, and rice husks (agricultural waste) can be effectively recycled and remanufactured into new materials. The construction industry requires a large amount of materials and energy throughout its lifecycle to ensure the normal operation of projects. However, as a major waste-producing industry, it still operates within a linear economic model (extract–use–dispose) without considering maximizing material preservation and reuse during the demolition process from the design and manufacturing stages. This results in construction materials becoming waste that cannot be reused in subsequent construction [16]. Therefore, material waste and increased carbon emissions in the construction industry had a double negative impact on the environment.

Management of construction waste and reducing GHG emissions during the operation and use phases of buildings has garnered attention from researchers. In terms of waste management, the Madaster platform registers buildings and establishes material passports for them, facilitating the exchange and reuse of materials through data management [17]. Additionally, assessments of building material stocks and waste disposal methods in larger areas using BIM (building information modeling) and GIS (geographic information system) technologies are beneficial for preparing for future waste and carbon emissions [18,19]. Zhu H. et al. developed a more precise method for building a framework for reusing building materials [20]. Energy consumption during building use is also a major source of greenhouse gases. The EU has utilized electricity usage data from the past decade to predict GHG emissions from building electricity consumption for better optimization and control [21]. Furthermore, the use of solar energy systems reduces the use of fossil fuels for heating in buildings [22,23]. Currently, various countries and regions have enacted regulations and standards to manage energy consumption during the operation of new buildings. In the renovation of old buildings, changes are made based on energy consumption during the use of roofing, windows and doors, insulation, heating and cooling systems, etc. [24]. In summary, the implementation of green building practices and the use of energy-saving equipment are crucial for reducing GHG emissions during the use of buildings through the optimization and upgrading of building technologies. However, if GHG emissions from materials, transportation, construction, and waste disposal can be estimated and

optimized at the beginning of building projects, controlling and reducing the generation of “embodied carbon” will make a significant contribution to reducing GHG emissions from buildings [25].

Currently, research primarily calculates carbon emissions from energy consumption during building operations [26], while the question of embodied carbon has not yet received sufficient attention. Constructing a low-carbon building space based on the CE concept requires systematic thinking about design methods, material sources, and reuse methods after the life cycle. Design is the starting point of the entire project process, and a good design can reduce 80% of negative environmental impacts [27] for reversible design or modular design and can make all components easier to assemble and disassemble so as to effectively improve the recycling rate of products. If recycled materials can be used on a larger scale, the exploitation of natural resources could be lessened, and the carbon dioxide emissions generated during material processing can be reduced by 40% to 70% [28]. Therefore, the use of new materials to replace industrial materials such as cement and steel will help achieve the zero-goal of the construction industry [29]. In the entire practice of innovative building cycles, the use of recycled materials and the calculation of embodied carbon emissions have enormous potential for GHG reduction.

This study, based on the CE concept in architectural practice, establishes the reversible design and carbon calculation (RDCC) method, systematically considering the circular practices of buildings. This method addresses design approaches (modular assembly and disassembly methods), material selection (recycled and biomass materials), and building dismantling (recycle and reuse), providing effective and feasible solutions for circular construction. RDCC increases the use of recycled materials throughout the entire building practice process, aiming to replace traditional materials with high GHG emissions to effectively reduce “Embodied Carbon” emissions. In addition to calculating GHG emissions during the manufacturing, transportation, production, and installation of building materials, this research also provides suggestions for the reuse of materials during recycling processes, thereby avoiding the generation of “embodied carbon” at the beginning of the building lifecycle [30]. Using the Circular Pavilion constructed in Guangzhou, China, as a practical case study, this research accurately predicts and calculates the total materials and accounts for the GHG emissions generated by different materials during production, transportation, and waste disposal. Through computer 3D modeling using Sketchup2023 and Rhino6 software, the study compares the Circular Pavilion, Concrete Pavilion, and Steel Pavilion in terms of material usage and carbon emissions during production, transportation, and waste disposal, resulting in 1595.68 kgCO₂e, 4522.95 kgCO₂e, and 46,895.84 kgCO₂e, respectively. The research indicates that the GHG emissions of the Circular Pavilion account for only 34% and 3.5% of the total carbon emissions of the Concrete Pavilion and Steel Pavilion, respectively.

2. Methodology

The impact of the application of recycled materials in architectural practice on reducing GHG emissions can be verified through the reversible design and carbon calculation (RDCC) method (Figure 1). The circular economy can be maximized through reuse and recycling so as to reduce the demand for new raw materials and improve the durability, maintainability, and recyclability of materials and products through design; thus, both the traditional linear economy’s exploitation of natural resources and the carbon emissions generated by large-scale processing of natural resources can be reduced [31]. On the one hand, employing reversible design methods involves considering the material selection, transportation methods, installation and dismantling processes, as well as the reuse methods after the lifecycle of the project from the design stage [32]. This aims to maximize the reuse of components and materials, reducing material waste and excessive production processing [33,34]. On the other hand, based on detailed material data from the design phase, using carbon emission calculation methods allows for an effective assessment of the total GHG emissions at the beginning of the project construction, thus effectively controlling the

generation of “embodied carbon”. These methods can immediately reduce carbon dioxide emissions, rather than relying on building performance and green operations to reduce emissions over the long-term use of the building.

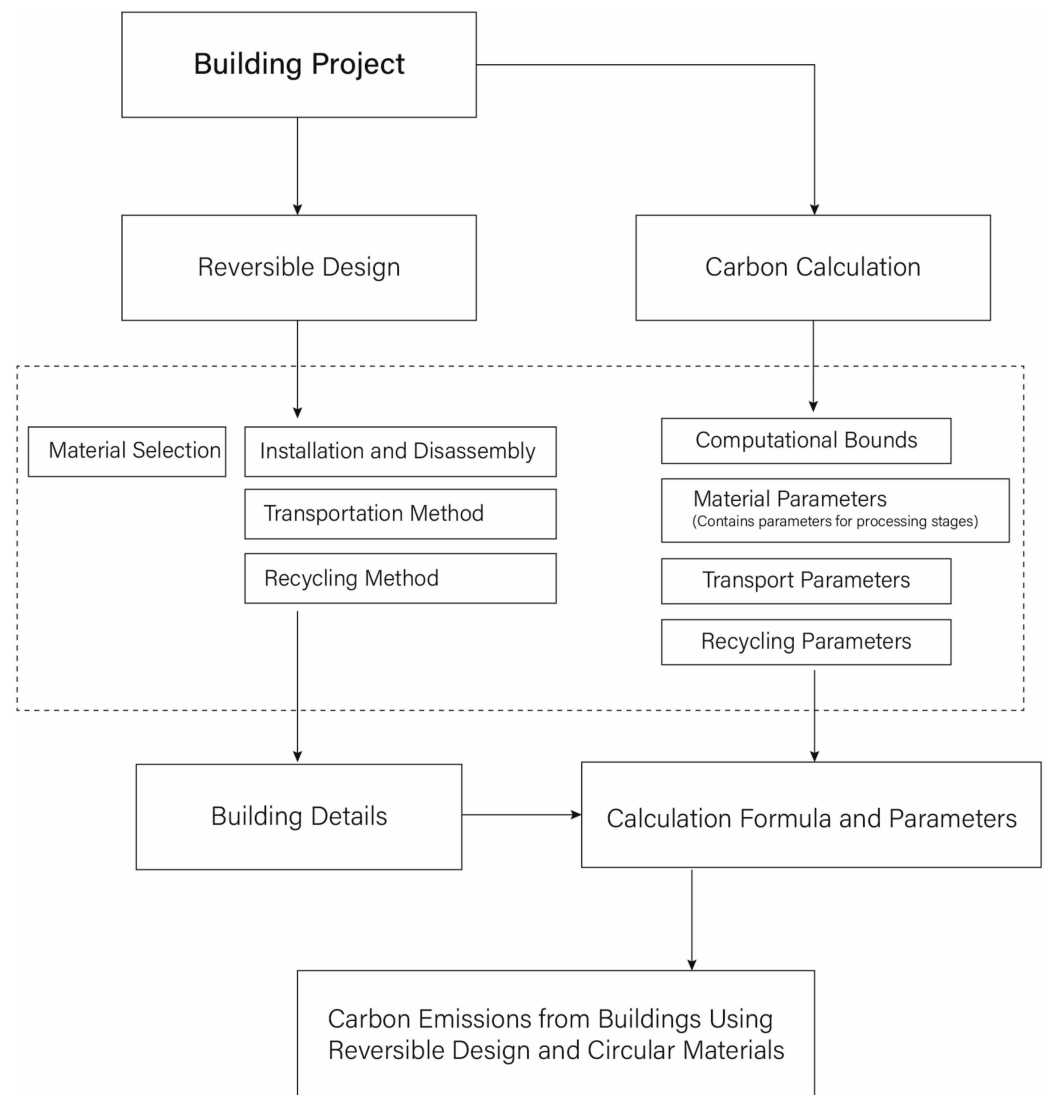


Figure 1. Systematic diagram of the reversible design and carbon calculation (RDCC) research method.

The RDCC method consists of two parts: (1) reversible design and (2) carbon calculation. This research believes that these two parts need to be carried out simultaneously. At the beginning of the building project, systematic consideration should be given to material selection, as well as the aspects of construction and potential impacts on GHG emissions during future dismantling. When the design is completed, the GHG emissions of the entire project are simultaneously calculated, and predictions are made for the reuse methods and GHG emissions after the end of the lifecycle, rejecting the approach of “pollution first, then treatment”.

2.1. Reversible Design Method

The purpose of reversible design (RD) is to increase the potential for the reuse of building components and materials and to reduce material waste during production through modularization, thereby enhancing transportation efficiency. It is important to emphasize the following: (1) In RD, a distinction should be made between demolition and dismantling. RD emphasizes dismantling (preserving materials or components as intact as possible) rather than demolition (destructive destruction) [35]; (2) modularization primarily refers

to dimensional modules of materials and components, reducing waste during material processing and improving efficiency during installation and transportation, thereby reducing GHG emissions. In this study, the focus of RD is on the recycling and reuse of building materials and components. SketchUp 3D modeling software was used at the beginning of the design phase to simulate the overall structure of the Circular Pavilion on a computer and to assess the feasibility of forward construction and reverse dismantling. Circular Pavilion was divided into six parts based on material types: (1) acoustic wood, (2) FSC-certified timber, (3) polycarbonate sheet, (4) recycled glass, (5) metal fasteners, and (6) steel column foundation (Figure 2). This was done to ensure that all stakeholders could clearly understand the overall situation of materials and components, including quantity, material, and installation location. Materials and components can not only be assembled together but can also be easily dismantled for replacement when damage occurs, or replacement is needed, facilitating circular reuse at the end of the lifecycle.

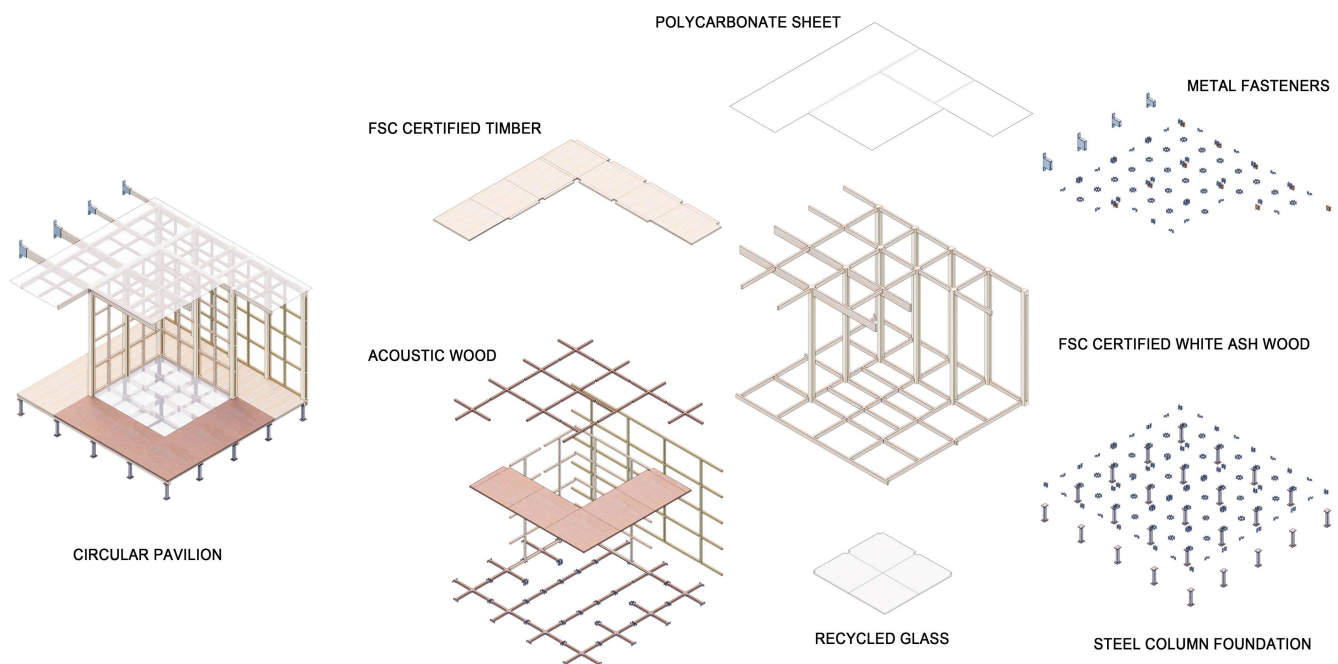


Figure 2. Diagram of construction and materials of Circular Pavilion.

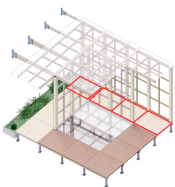
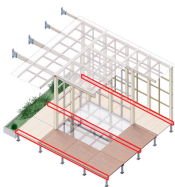
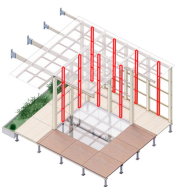
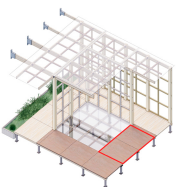
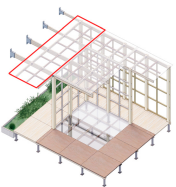
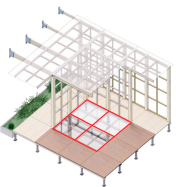
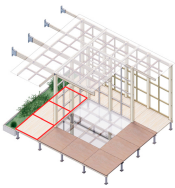
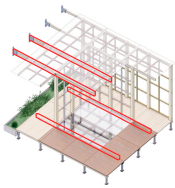
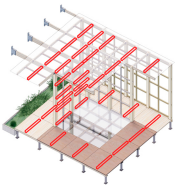
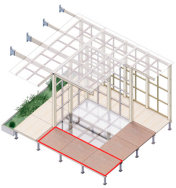
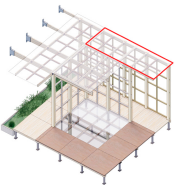
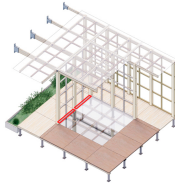
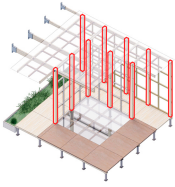
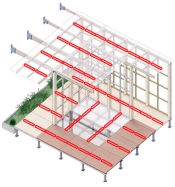
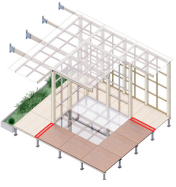
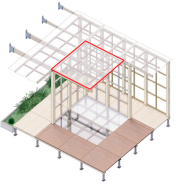
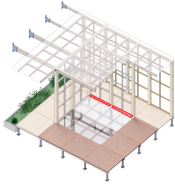
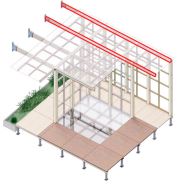
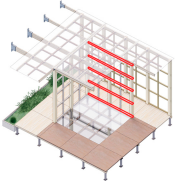
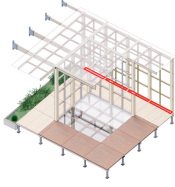
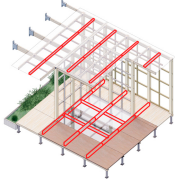
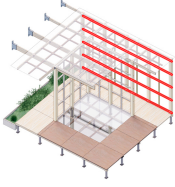
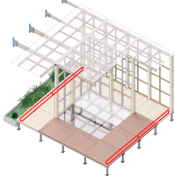
Detailed material and component statistics can enhance the potential for reuse. In this study, during the design phase of the Circular Pavilion, different recycled materials were selected based on the functional characteristics of different spaces. Materials were classified, numbered, and carefully counted according to material type and usage, as shown in Table 1.

The table assigns numbers to indicate the locations of the main materials used in the Circular Pavilion project:

- (1) Forest Stewardship Council (FSC) certification is an environmentally friendly solid wood certification standard. FSC-certified timber (FCT) is the component name. “G” indicates that the component is used on the ground, while “S” indicates that the component is used in the primary structure of the Circular Pavilion.
- (2) Rice hull composite (RHC) is a material made from recycled rice husks (agricultural waste). RHC-G is used on the ground, while RHC-S is used in secondary structures.
- (3) Recycled multiwall polycarbonate (RMP-C) sheets utilize offcuts from the manufacturing process, with a proportion exceeding 30%. It is only used on the ceiling.
- (4) Recycled glass panel (RGP-G) is made from recycled glass bottles in this study, with 47% of green energy used in the processing and melting temperature reduced to

900–1000 degrees Celsius. Due to the heavy weight of the material, RGP-G is used on the ground portion.

Table 1. Circular Pavilion material location description table.

Number	FCT-G	FCT-S	RHC-S	RHC-G	RMP	RG-G
a						
b						N/A
c						N/A
d				N/A	N/A	N/A
e				N/A	N/A	N/A
f	N/A		N/A	N/A	N/A	N/A

Prepared by the author.

Based on detailed computer-simulated 3D digital models and comprehensive material inventory tables, it is possible to provide a basis for GHG emissions, transportation methods, recycling methods, and waste disposal methods during the design phase. In Table 2, detailed statistics are provided for the density, total weight, quantity, and specific dimensions of the materials. Additionally, materials are assigned numbers for cross-referencing with their locations within the Circular Pavilion.

Table 2. Circular Pavilion material classification and statistical table.

Material	Item Number	Weight (Unit: kg)	Quantity (Unit: Piece)	Dimension (Unit: mm)
FSC-certified timber— ground/structural frame Density: 675 kg/m ³	FCT-G-a	162.73	4	1230 × 980 × 50
	FCT-G-b	139.73	3	1150 × 1200 × 50
	FCT-G-c	4.39	2	980 × 65 × 50
	FCT-G-d	5.94	2	1100 × 80 × 50
	FCT-G-e	14.45	4	1070 × 100 × 50
	FCT-S-a	55.69	3	5000 × 110 × 50
	FCT-S-b	71.28	4	4800 × 110 × 50
	FCT-S-c	241.31	20	3250 × 110 × 50
	FCT-S-d	44.62	2	6010 × 110 × 50
	FCT-S-e	113.31	28	1090 × 110 × 50
	FCT-S-f	33.12	4	2230 × 110 × 50
Rice hull composite—structural frame/ground Density: 83.33 kg/m ³	RHC-S-a	4.65	32	700 × 50 × 50
	RHC-S-b	6.85	33	1000 × 50 × 50
	RHC-S-c	5.93	52	550 × 50 × 50
	RHC-S-d	2.10	4	2500 × 50 × 50
	RHC-S-e	5.19	5	5000 × 50 × 50
	RHC-G-a	10.96	2	1200 × 1100 × 50
	RHC-G-b	17.93	3	1200 × 1200 × 50
	RHC-G-c	1.12	2	1120 × 120 × 50
Circular multiwall polycarbonate—ceiling Density: 12 kg/m ³	RMP-C-a	0.86	1	4780 × 1500 × 2
	RMP-C-b	0.59	1	3700 × 1330 × 2
	RMP-C-c	0.61	1	2400 × 2100 × 2
Recycled glass panel—ground Density: 1850 kg/m ³	RG-G-a	506.16	4	1200 × 1140 × 50

Prepared by the author.

Detailed material data allows for the accurate calculation of the volume of different materials. When combined with the density of each material, it becomes possible to estimate the overall weight of the materials, providing a basis for calculating the total greenhouse gas emissions. As building materials typically have relatively large dimensions, it is challenging to use weighing methods without additional mechanical equipment. Therefore, the weight of the materials in this study is determined by multiplying material volume by material density. While the calculated material weight based on volume and density may have some deviation from the actual weight, the impact on the final data is relatively small.

In the dismantling process of the Circular Pavilion, this study employed on-site research methods (Figure 3), meticulously documenting materials or components damaged during use and cross-referencing with the Sketchup2023 and Rhino6 3D modeling software and material inventory table. The dismantling process followed a reverse order from the original construction sequence. Initially, recycled glass, rice hull composite panels, and FSC-certified larch boards were removed from the ground. Then, decorative materials were dismantled, followed by the removal of beams, columns, and ground structures from top to bottom. Additionally, materials were sorted and recorded based on their type, size, and extent of damage.

2.2. Calculation Method for Carbon Dioxide Emissions Volume

2.2.1. Computational Boundary

The construction industry produces carbon dioxide emissions mainly in four stages: material production stage, construction stage, building operation stage, and building dismantling stage [36]. Among them, the coefficient of raw material production includes electricity and transportation (transportation here is from the origin to the factory), so there is no need to additionally calculate electricity emissions and transportation emissions from the origin to the factory; in the waste treatment stage, the carbon coefficient will

change depending on the recycling method (for example, structures made entirely of wood are to be incinerated, steel structures are to be returned to the furnace, plastics are to be recycled, and ordinary glass is to be landfilled). It is also necessary to calculate the carbon emissions generated by the transportation of the treatment project at this stage. The purpose of this study is to demonstrate that the use of reversible design methods and recycled materials can reduce GHG emissions during the practical process of building construction. However, the factors influencing GHG emissions during the operation and construction stages of buildings are diverse, leading to greater uncertainty in the results of this study. Therefore, an open public building was chosen as the subject of this study, and the case study did not involve the installation of cooling, heating, or other equipment systems. Additionally, the construction process mainly relied on manual installation without the use of large machinery or power tools. Consequently, GHG emissions during the construction and operation stages of the building were excluded from the study, and GHG emission calculations primarily focused on the material production and building dismantling stages. In order to better compare the carbon emission impacts of different materials, this study method involved comparing the same Pavilion, utilizing identical component dimensions, assembly processes, and construction techniques while employing different building materials. This approach aimed to eliminate the influence of other differences on the research data. The focus was on discussing the GHG emissions data resulting from the use of reversible design and recycled materials in the production and disposal stages.



Figure 3. Disassembly process of Circular Pavilion ©REDO Design Corporation, Guangzhou, China.

2.2.2. Calculation Formula

It is very important to calculate the GHG emissions of an upcoming or ongoing project based on detailed project information. It is required to make an effective assessment of the environmental impact of the materials and manufacturing methods used so as to better select materials and outstanding suppliers. Referring to the assessment method of the full life cycle carbon emissions of products and services provided by PAS 2050:2011 [37] (publicly available specification) and ISO 14067:2018 [38], this study collects the material quantity data in the project and then multiplies it by the corresponding carbon coefficient of different materials, and finally adds the carbon coefficient of transportation (Formula (1)); therefore, the computational method is displayed as follows:

$$E = \Sigma (m \times EF_i + d \times EF_j) \quad (1)$$

where E refers to the GHG emissions volume, m represents the mass of the used material, EF_h is the GHG emissions coefficient of the material, d is the transportation distance, and EF_i is the carbon GHG coefficient of transportation. However, in addition to the calculation of GHG emissions in the material production stage Σ_1 (including transportation), the calculation of GHG emissions in this study project also includes the emissions of some materials in the waste treatment stage Σ_2 (Formula (2)). Therefore, the calculation approach in this project is:

$$E = \Sigma_1(m \times EF_h + d \times EF_i) + \Sigma_2(n \times EF_j + p \times EF_k) \quad (2)$$

where n is the mass of waste materials that need to be incinerated, EF_j is the carbon dioxide emissions coefficient of material to be incinerated, p is the mass of waste materials that need to be landfilled, and EF_k is the GHG emissions coefficient of material to be landfilled.

3. Results

According to the survey data on the partial material damage of the Circular Pavilion onsite (Table 3), materials used on the ground and ceiling are more prone to damage because they are more susceptible to environmental erosion. Next are the main structural components, whose damage is mainly due to human factors, as some materials were damaged due to workers' unfamiliarity with the dismantling sequence during dismantling. This study incorporates the GHG emission data of damaged materials into the total GHG emissions during the disposal stage.

Table 3. Table of damaged materials in Circular Pavilion.

No.	Quantity (Unit: Piece)	Size (Unit: mm)	Weight (Unit: kg)	Location	Cause of Damage
FCT-G-a	2	1230 × 980 × 50	81.36	Use on the ground	Rain and exposure
FCT-G-b	1	1150 × 1200 × 50	46.58		
FCT-G-d	1	1100 × 80 × 50	2.15		
FCT-G-e	1	1070 × 100 × 50	3.61		
FCT-S-e	2	5000 × 50 × 50	8.09	Used structurally	Demolition
RHC-S-a	3	700 × 50 × 50	0.44		
RHC-S-b	2	1000 × 50 × 50	0.42		
RHC-S-c	3	550 × 50 × 50	0.34		
RMP-C-a	1	3700 × 1330 × 2	0.86	Used on ceiling	Heavy rain and fierce wind

Prepared by the author.

The GHG emission factors of the materials used in this study are listed in Table 4, explaining the GHG emission factors of different building materials in the production and disposal stages. This dataset is compiled based on publicly available literature and data from the China Product Lifecycle Greenhouse Gas Emission Coefficients Collection [39], the UK Government GHG Conversion Factors for Company Reporting [40], and the IPCC dataset [41]. Since rice hull composite does not have explicitly stated GHG emission data in the relevant datasets and literature, this paper reassesses and calculates the GHG emissions of composite materials in the production stage based on the material type and composite ratio: 30% plastic: 70% rice hulls. The carbon emission factor (CEF) for rice hulls should be chosen when rice hulls are obtained, i.e., the CEF for rice hulls when rice is produced and husked. There is no statistical data available for the CEF when plastic and rice hulls are synthesized into composite materials, so it is not included in the calculation for this study. Therefore, the CEF for rice hull composite materials is calculated as follows: plastic carbon emission factor × 30% plastic mass + rice hull CEF × 70% rice hull mass, which is equal to 1.004887 kg CO₂-eq/kg. Additionally, since both rice hull composite and polycarbonate are new recycled materials, the material densities are calculated based on the dimensions and masses of the materials. Therefore, the densities of the two materials were calculated by

weighing a flat sample measuring 10 cm × 10 cm × 2 cm: 83.33 kg/m³ and 12 kg/m³. The densities of other materials were calculated using standard material density values.

Table 4. Carbon emission factors and density of different materials of Circular Pavilion in the production and waste treatment stages.

Category	Concrete	Metal	Composite Material	Glass		Plastic	Wood	
	Common Concert	Carbon Steel	Rice Hull Composite	Ordinary Glass	Recycled Glass	Polycarbonate	Reclaimed Wood	Virgin Wood
CEF during production (Unit: kgCO ₂ -eq/kg)	0.7406	2.42	1.004887	1.4028	0.8232	1.37	0.2591	0.3126
Density (Unit: kg/m ³)	2000–2800, 2400 as the median	7850	83.33	2400–2800, 2600 as the median	1800–1900, 1850 as the median	12	675	
Disposal method	Landfill	Remelting Closed-loop	N/A	Landfill	N/A	Combustion	Combustion	
CEF during disposal (Unit: kgCO ₂ -eq/kg)	0.00124	0.00099	N/A	0.0089	N/A	0.0599	0.3844	

Prepared by the author.

During the study process, the materials used in the construction of the Circular Pavilion were all local materials, so China-related datasets were given priority in the study. If there were no corresponding Chinese datasets, other relatively complete GHG emission datasets were used. Although it is not possible to obtain public data on the density of composite materials, their relevant values were measured according to the actual specification and weight of the material in the study. There may be some errors in this process, but it does not affect the integrity of the overall data.

Detailed material dimensional statistics organized using the RDCC method can accurately determine the vehicles used during transportation. The specifications and carbon dioxide emission factors of freight vehicles are listed in Table 5 according to the vehicle carbon dioxide emission factors of road traffic in China by province [42]. By the time of actual implementation of this research project, the maximum size of the FSC solid wood materials used exceeds 6 m, and the total mass is less than 1000 kg, so medium-sized trucks need to be used as transportation vehicles; in the same case, the RHCs are transported using a light truck, while the multi-layer polycarbonate panels and recycled glass are transported using a minivan.

Table 5. China road freight vehicle specifications and CO₂ emission factors (incl. Guangdong).

Vehicle Type	Fuel	Classification Criteria	Full Load	CO ₂ Emission Factor (Nationwide)	CO ₂ Emission Factor (Guangdong)
				Unit: kgCO ₂ /(t·km)	Unit: kgCO ₂ /(t·km)
Heavy truck	Diesel	Maximum allowed total mass > 12,000 kg	18 t	0.049	0.048
Medium-duty truck		Vehicle length > 6000 mm or 4500 kg < Maximum allowed total mass < 12,000 kg	12 t	0.042	0.042
Light truck		Vehicle length < 6000 mm or Maximum allowed total mass < 4500 kg	4.5 t	0.083	0.083
Mini truck		Vehicle length < 3500 mm or Maximum allowed total mass < 1800 kg	1.8 t	0.12	0.119

Prepared by the author [42].

As for the material data and transportation data, in addition to the recycled materials used in the project, relevant data on steel and concrete materials are also included in order to compare the GHG emissions volume of different materials during construction practice. In GB26408-2020 Concrete truck mixer [43], it is stated that the measurement of exhaust pollutants is in accordance with GB17691-2018 Limits and measurement methods for emissions from diesel fueled heavy-duty vehicles (CHINA VI) [44] and GB20891-2014 Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery (CHINA III, IV) [45]. Therefore, the carbon dioxide emissions data of concrete transport vehicles are calculated based on the data of heavy-duty trucks. In addition, the carbon dioxide emission factor of freight vehicles is described based on the carbon dioxide emission factor when the vehicle is fully loaded. In this study, it is assumed that the vehicles transport goods at full capacity, although the frequency and distance of vehicle transport are relatively low, so they are not expected to significantly impact the calculation results.

The study compared the difference in GHG emissions between buildings using the RDCC method and traditional building materials (steel and concrete) not using the RDCC method. As shown in Figure 4, the GHG emissions were calculated for the same Pavilion under the same building structure and usage conditions across three lifecycle stages: production, disposal, and transportation. For the Circular Pavilion using the RDCC method, the GHG emissions were calculated as follows: 1537.54 kgCO₂e for production, 3.37 kgCO₂e for transportation, and 54.78 kgCO₂e for disposal, resulting in a total GHG emission of 1595.68 kgCO₂e. In contrast, the total GHG emissions for the Concrete Pavilion and Steel Pavilion were 4522.95 kgCO₂e and 46,895.84 kgCO₂e, respectively. The total GHG emissions of the Concrete Pavilion and Steel Pavilion were 2.83-fold and 29.39-fold higher, respectively, compared to the Circular Pavilion. The data clearly indicate that the use of recycled materials in building practices can significantly reduce GHG emissions.

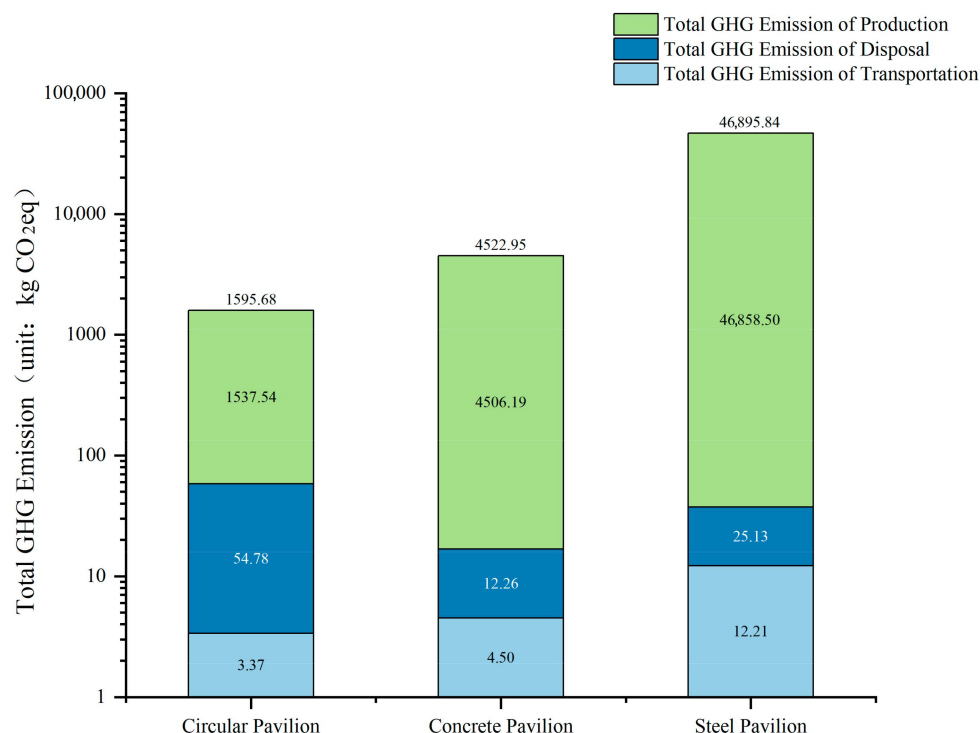


Figure 4. Total carbon dioxide emissions volume of Circular Pavilion\Concrete Pavilion\Steel Pavilion.

Furthermore, based on the research data, GHG emissions generated during the building material production stage account for over 95% of the total emissions. Material selection plays a significant role in influencing the GHG emissions of buildings during the production, disposal, and transportation stages. In the production stage (Figure 5), carbon

steel GHG emissions are the highest, reaching 45,857.81 kgCO₂e, followed by concrete GHG emissions at 3505.50 kgCO₂e. The differences between common glass, recycled glass, and rice hull composite are relatively small, at 997.87 kgCO₂e, 710.03 kgCO₂e, and 547.58 kgCO₂e, respectively. The lowest GHG emissions are from polycarbonate, at only 2.82 kgCO₂e. Although the total GHG emissions of these materials are influenced by their overall usage during construction, when comparing GHG emissions of the same quantity of materials in the same location, recycled materials still exhibit relatively lower GHG emissions.

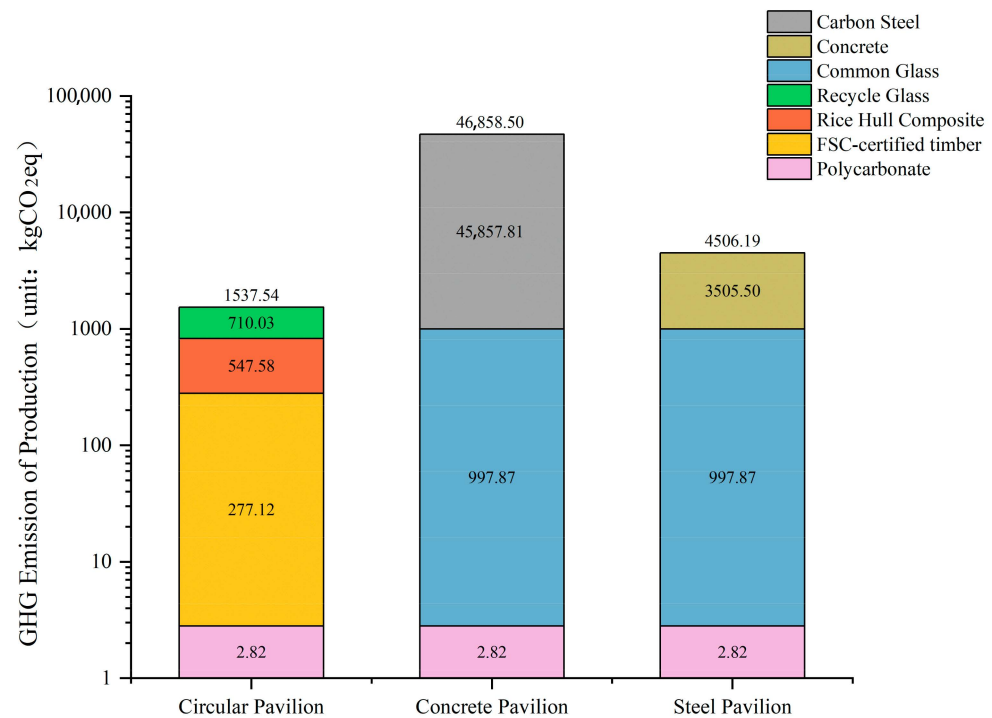


Figure 5. Pavilion materials' GHG emissions from the production stage.

It should be emphasized that if we use a more macroscopic mindset to consider the production and disposal stages of non-native materials, they are interrelated and interdependent. If we can reduce material waste in the disposal stage and increase material recycling rates, we can relatively reduce the GHG emissions from the production stage of non-native materials. In this study, it is assumed that the concrete and steel materials in the Concrete Pavilion and Steel Pavilion are 100% recycled using traditional recycling methods (landfill and smelting). However, the Circular Pavilion includes the GHG emissions generated from the damaged parts during use or dismantling, mainly FSC-certified timber, which is to be incinerated. Therefore, in the disposal stage, the GHG emissions from FSC-certified timber used in the Circular Pavilion are 54.51 kgCO₂e, exceeding those from carbon steel, common glass, and concrete used in the Concrete Pavilion and Steel Pavilion (Figure 6).

Differences in material specifications (length, weight, volume, etc.) can result in varying amounts of GHG emissions due to differences in the vehicles used. Therefore, modular dimensions and lighter weight can both reduce GHG emissions during transportation. This aspect can be considered during the design process to choose the optimal transportation vehicle solution. On the other hand, the impact of transportation distance on GHG emissions cannot be ignored. In Figure 7, the transportation GHG emissions for the materials used in this research project are relatively low because materials were chosen from factories located closer to the project site, minimizing the distance materials need to travel from the factory to the project site and effectively controlling GHG emissions generated during transportation. This also underscores the need to consider the overall impact of materials

at various stages comprehensively and from a macro perspective rather than singularly evaluating their impact from one dimension as large or small.

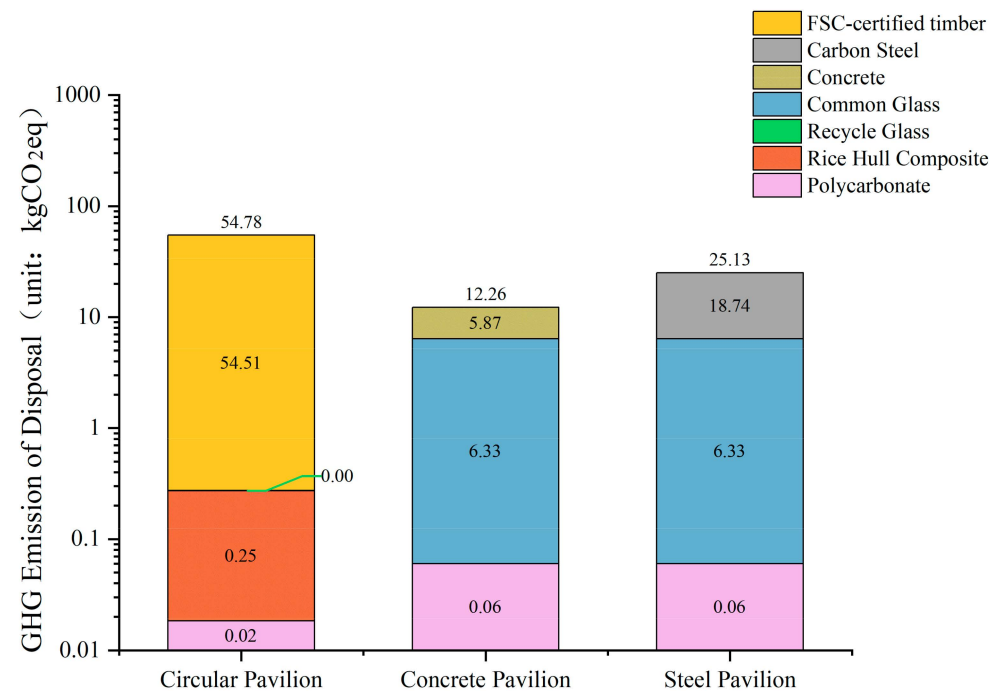


Figure 6. Pavilion materials' GHG emissions from the disposal stage.

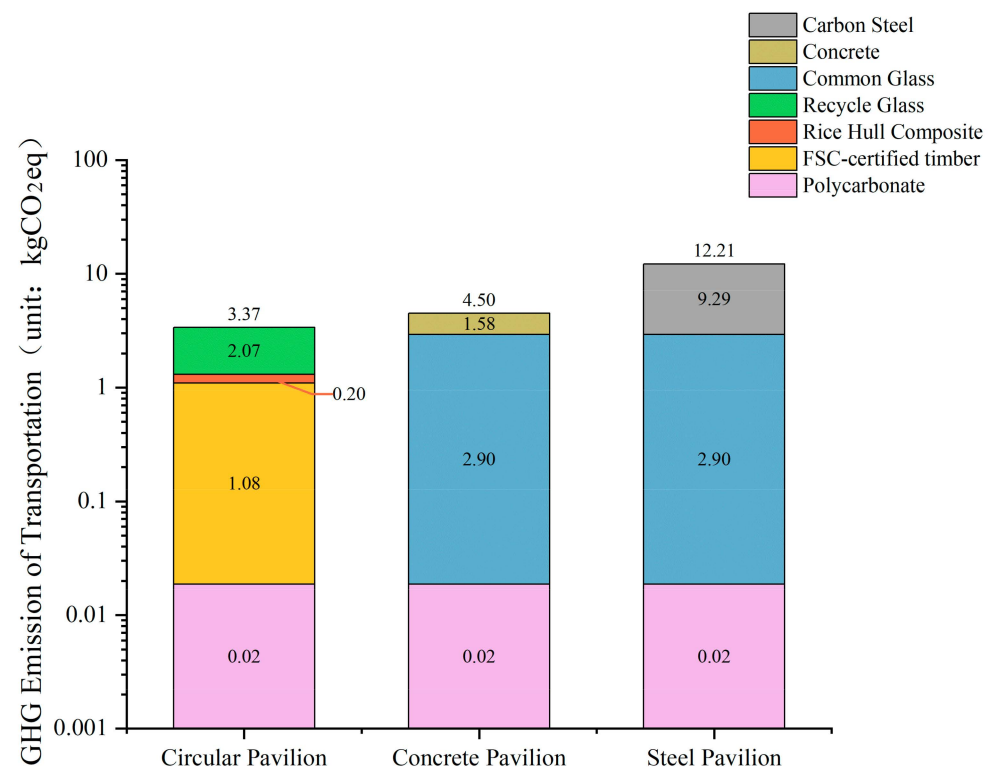


Figure 7. Pavilion materials' GHG emissions from the transportation stage.

In this study, apart from FSC-certified timber, which has a relatively low recycling value and is commonly disposed of through incineration, concrete is primarily disposed of through landfilling, while steel is recycled by remelting. Rice hull composite, glass, and polycarbonate are already widely recycled and reused in the industry. A complete supply

chain is crucial in promoting the application of recycled materials, which is a significant factor contributing to the reduction of GHG emissions during the disposal phase for these materials.

4. Discussion

Research on the cyclical, sustainability, and reduction of GHG emissions in buildings has garnered more attention from researchers, including various directions such as architectural design, building restoration, construction techniques, materials science, and energy systems. These studies primarily focus on rating tools and life cycle methods (including LCA and LCC) [46–48]. In addition to evaluation methods, design methods have been proposed to reduce the amount of materials used and promote the direct reuse of materials by repair, renovation, or repurposing [49], as well as the dismantling of buildings at the end of their life cycle to improve the utilization of building materials [50–53]. In most cases, both research methods and frameworks make partial assumptions about research cases or simulate real situations through computer models. However, the influence of external factors can lead to deviations in future building practices. For instance, in this study, (1) the quantity of damaged FSC-certified timber increased due to non-standard construction operations; (2) FCT was used on the main structure of the Circular Pavilion to enhance its structural stability, as its material strength is slightly lower than that of RCH; and (3) instances of partial material damage reveal that wooden surface materials are more susceptible to damage from weather conditions such as rain, sun exposure, and strong winds, as evidenced by issues like partial waterlogging due to uneven terrain, damages and deformation caused by sunlight exposure, and direct destruction caused by strong winds, demonstrating the importance of research combined with practice. Moreover, “upstream innovation” will have a more direct impact on controlling GHG emissions in future new construction projects. It can utilize design methods to reduce the “prepayment” of greenhouse gases from the beginning stage of building implementation, which differs from “downstream innovation” concerning the dismantling, renewal, and maintenance of existing buildings, representing a long-term, persistent effort. In the future, there is a need for more extensive practice in circular building construction to provide a basis for the application of circular materials in the construction industry while also providing data support for research on GHG emissions from buildings.

5. Conclusions

Sustainable development is gradually becoming an important goal for human society. More and more researchers and industry practitioners are considering the CE as an effective solution to reverse the negative impact of the construction industry on the environment. This study demonstrates that reversible design methods and recycled materials can reduce GHG emissions in construction practice. Through the complete practice steps of “design, material selection, transportation, construction, and dismantling” of the Circular Pavilion, including simulation, statistics, and on-site research, the total GHG emissions of the Circular Pavilion were calculated. Three different building materials were compared in terms of GHG emissions at various stages of construction for the pavilions. The results show that the Concrete Pavilion and Steel Pavilion emit 284% and 2939% more greenhouse gases, respectively, compared to the Circular Pavilion, which uses recycled materials. This also proves that using recycled materials can replace traditional building materials, thereby reducing the “prepayment” of greenhouse gases, which takes effect immediately. This study differs from Madaster’s method of registering building materials and using GIS to statistically analyze urban minerals, in which it evaluates the reuse value and reuse potential of materials, items, and components only at the end of the building’s lifecycle. This research took one year to practice and test the complete process of building and dismantling the Circular Pavilion. Future research needs to increase the number of times materials are reused and their duration of use to obtain more data on the weather resistance and durability of recycled materials.

Different materials or transportation methods will have an impact on GHG emissions. Using reversible design methods and recycled materials can increase the reuse rate of building components and reduce GHG emissions during the production phase. However, it was found during the research process that obtaining carbon emission factors for recycled materials is difficult, and there are also differences in materials and transportation methods due to different countries and regions. Currently, the types of materials in commonly used databases still need further supplementation from governments, institutions, and researchers.

Although the construction and dismantling stages have a relatively low proportion of GHG emissions throughout the building's lifecycle, this process can have significant marginal effects that are easily overlooked. Even though detailed objectives for forward installation and reverse dismantling were established during the research process, and the entire process was simulated using computer 3D modeling, stronger project management intervention is necessary to achieve these goals. Because construction workers do not have anticipated motivation for the entire project implementation, there are differences between the installation sequence and the plan, leading to component damage during later dismantling and increasing GHG emissions during the disposal phase. This problem may be widespread in the construction practice process. Future research should incorporate project implementation management methods into reversible design methods to enhance the unity of design and management.

Various studies have pointed out that the construction industry is currently a major source of GHG emissions, with the production of building materials accounting for the highest proportion of emissions throughout the entire building lifecycle (material production, operation, construction, dismantling). Some studies have also significantly promoted the goal of the construction industry moving towards low-carbon development by increasing the durability of building materials, upgrading building door and window systems and equipment systems to reduce energy consumption during the operational phase, and even enhancing the value of building waste through different strategies. We need to integrate and optimize different aspects of the building lifecycle, considering not only strategies but also the potential marginal effects that may arise during the practical implementation process. This study provides a real and feasible case for the application of reversible design in architectural practice and provides evidence for the reduction of GHG emissions through the use of recycled materials.

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Nomenclature

CE	Circular Economy
GHG	Greenhouse Gas
BIM	Building Information Modeling
GIS	Geographic Information System
RDCC	Reversible Design and Carbon Calculation
RD	Reversible Design
FSC	Forest Stewardship Council
FCT	FSC Certified Timber
RHC	Rice Hull Composite
RMP	Recycled Multiwall Polycarbonate
RGP	Recycled Glass Panel
IPCC	Intergovernmental Panel on Climate Chang
CEF	Carbon Emission Factor
LCA	Life Cycle Assessment
LCC	Life Cycle Costing

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